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Arctic Marine Design and Construction Handbook

Volume 1
Final Report

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September 1984

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The contents of this report reflect the views of the contractor and not necessarily the official views or policies of the Transportation Development Centre of Transport Canada.

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T.F. Saunders, P. Eng.
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17. Abstract

This reference document, in two volumes, provides a compendium of information and current practice in the design and construction of Arctic marine structures. It presents information on the Canadian Arctic related to economic resources, environmental, ice and geotechnical conditions and provides essential technical information upon which design criteria for wind, waves, currents, snow loads, ice forces and geotechnical conditions are based. It discusses existing engineering guidelines, regulations, standards and various options for the design and construction of ice resistant structures and identifies information deficiencies in these areas and indicates where research and development is required. A selective, annotated bibliography, sources and titles of pertinent technical publications and a list of agencies and organizations providing information on the Arctic, are also provided.

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17. **Résumé**

Cet ouvrage en deux tomes constitue un recueil théorique et pratique des méthodes de conception et de construction de structures maritimes dans l'Arctique. Il renseigne sur la région arctique du Canada: ressources, économie, conditions environnementales, glacielles et géotechniques et présente les données techniques de base ayant servi à l'élaboration des critères de calcul relatifs aux forces exercées par le vent, la houle, les courants, les glaces, la neige et aux conditions géotechniques. Il traite de la réglementation, des guides et des normes en vigueur concernant la conception et la construction de structures à l'épreuve des glaces; souligne les lacunes constatées dans les divers domaines abordés et met en évidence les secteurs où des travaux de recherches et développement sont nécessaires. Il comporte une bibliographie annotée d'ouvrages sélectionnés, donne le titre et la maison d'édition des diverses publications intéressant le domaine considéré et dresse la liste des sociétés et organismes susceptibles de renseigner les intéressés sur tout ce qui touche à l'Arctique.

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CANADIAN ARCTIC MARINE DESIGN AND CONSTRUCTION HANDBOOK

PREFACE

This handbook presents in two volumes a compendium of information and current practice in the design and construction of marine structures in the Canadian Arctic. The term "Arctic Marine Structures" is defined for the purpose of this handbook, as marine civil structures essential for secure berthing of vessels and transfer of cargo between vessels and a terminal.

The objectives of this handbook are:

1. To consolidate in one document existing knowledge related to the design and construction of Arctic marine structures.
2. To provide a useful reference document for planners, engineers and contractors.
3. To provide a basis for establishing design standards, guidelines and regulations for Canadian Arctic marine construction.
4. To identify gaps in current knowledge of ice engineering and/or Arctic marine design and construction practice.
5. To establish priorities for future research and development in the field of Arctic marine structures.

Volume 1 provides an overview of current Arctic technology as it applies to Arctic marine structures. Chapter contents are summarized as follows:

Chapter 1 presents background information on the Canadian Arctic as related to economic resources and environmental conditions. Basic functional requirements and types of port related civil engineering structures for the Arctic are identified.

Chapter 2 describes the Canadian Arctic marine environment and presents information on wind, waves, currents, snow, and other climatic and oceanographic phenomena.

Chapter 3 presents major aspects of ice technology and provides technical information upon which ice design criteria in the Canadian Arctic are based.

Chapter 4 defines Arctic geotechnical conditions and presents information on permafrost. The geotechnical design aspects of structures in permafrost are discussed. Information on instrumentation and monitoring of structures affected by geotechnical considerations are presented.

Chapter 5 discusses responses to the Arctic ice environment. Ice control techniques are identified and various options for ice resistant structures are presented.

Chapter 6 presents existing regulations and standards for Arctic marine structures.

Chapter 7 presents design guidelines for Arctic marine structures based upon existing state of the art design practice.

Chapter 8 presents an outline of construction procedures and techniques currently utilized in the Arctic.

Chapter 9 presents an inventory of existing Arctic marine facilities.

Chapter 10 identifies information deficiencies and indicates those areas where research and development are required to upgrade existing knowledge in the design and construction of Arctic marine facilities.

Volume 2 provides a selected inventory of technical data which is most likely to be of value to engineers and contractors working on Arctic marine projects. The volume contains lists of technical publications, according to subject, followed by the abstracts of the listed publications. The appendix portion, in four parts, provides sources of information on the Arctic, as follows:

- List of regulatory agencies and organization, with latest addresses
- List of additional useful references
- List of technical conferences, of interest to the Arctic engineering
- List of Companies providing sealift transportation in the Canadian Arctic

ARCTIC MARINE DESIGN AND CONSTRUCTION HANDBOOK

TABLE OF CONTENTS

VOLUME I

Page

1.0 INTRODUCTION 1

1.1 Arctic Opportunities 1
  1.1.1 Resources in the Arctic 1
  1.1.2 Oil and Gas in Ice Affected Areas 1

1.2 Pertinent Canadian Arctic Regions 4
  1.2.1 Regions Based on Ice Variations 4
  1.2.2 Physiographic Regions 4
  1.2.3 General Climate 5

1.3 Functional Requirements 6
  1.3.1 Vessel Characteristics 7
  1.3.2 Marine Terminal Components 7

1.4 Types of Structures 11
  1.4.1 Bottom Founded Marine Structures 12
    1.4.1.1 Unconfined Fill islands 12
    1.4.1.2 Confined Fill Structures 12
    1.4.1.3 Prefabricated Gravity Structures 14
    1.4.1.4 Pile Structures 14
    1.4.1.5 Jacket Structures 15
    1.4.1.6 Jack-Ups 15
    1.4.1.7 Grounded Ice Islands 15
    1.4.1.8 Shoreline Structures 15

TABLE OF CONTENTS (Cont'd)

Page

1.0 INTRODUCTION (Cont'd)

1.4.2 Floating Structures 15
  1.4.2.1 Barges 15
  1.4.2.2 Semi-Submersibles 15
1.4.3 Subsea Structures 15
  1.4.3.1 Single Point Mooring Terminals 15
  1.4.3.2 Pipelines 15

1.5 Logic for Planning and Design 15

2.0 MARINE ENVIRONMENT 18

2.1 Bathymetry 18
2.1.1 Arctic Archipelago 18
2.1.2 Beaufort Sea 18
2.1.3 Hudson Bay 19
2.1.4 Baffin Bay 19
2.1.5 Labrador Shelf 19

2.2 Meteorology 19
2.2.1 Atmoshperic Factors 19
  2.2.1.1 Air Temperatures 19
  2.2.1.2 Precipitations 25
  2.2.1.3 Barometric Pressures 31
  2.2.1.4 Winds Including Effect on Ice 31
  2.2.1.5 Humidity 42
2.2.2 Visibility Factors 42
  2.2.2.1 Daylight 42
  2.2.2.2 Visibility Restrictions 42

TABLE OF CONTENTS (Cont'd)

Page

2.0 MARINE ENVIRONMENT (Cont'd)

2.2.3 Snow Loads 47
2.2.4 Superstructure Icing 47

2.3 Oceanography 50
2.3.1 Sea Water Characteristics 52
2.3.2 Currents and Circulations 52
2.3.3 Tides 62
2.3.4 Waves 63
2.3.4.1 Wave Climate 63
2.3.5 Wave Forces 63

3.0 ICE TECHNOLOGY 71

3.1 Morphological Properties of Ice 71
3.1.1 Atomic Structure of Ice 71
3.1.2 Definition of Ice Types 72
3.1.3 Structural Development of Various Types of Ice 72
3.1.3.1 Pure Ice 72
3.1.3.2 Fresh Water Ice 74
3.1.3.3 Sea Ice 75
3.1.4 Characteristics of Ice Found in Sea Water 77
3.1.4.1 Multi Year Ice 77
3.1.4.2 Pressure Ridges and Rubble and Hummock Fields 77
3.1.4.3 Icebergs and Ice Islands 79

TABLE OF CONTENTS (Cont'd)

Page

3.0 ICE TECHNOLOGY (Cont'd)

3.2 Mechanical Properties of Salt Water Ice 80
  3.2.1 Parameters of Importance 80
    3.2.1.1 Grain Size and Crystal Orientation 80
    3.2.1.2 Brine Volume 81
    3.2.1.3 Strain or Stress Rate 81
    3.2.1.4 Scale Effects 87
    3.2.1.5 Temperature Effects 88
    3.2.1.6 Confinement 90
  3.2.2 Strength Properties of Salt Water Ice 90
    3.2.2.1 Compressive Strength 90
    3.2.2.2 Tensile Strength 93
    3.2.2.3 Flexural Strength 94
    3.2.2.4 Fracture Toughness 95
  3.2.3 Deformational and Shear Properties 97
    3.2.3.1 Elastic Modulus 97
    3.2.3.2 Poisson's Ratio 99
    3.2.3.3 Thermal Expansion and Other Properties 99
  3.2.4 Adhesion and Friction 99
  3.2.5 Mechanical Properties of Low and Non-Saline Ice 100
    3.2.5.1 Grain Size and Crystal Orientation 100
    3.2.5.2 Porosity 102
    3.2.5.3 Strain or Stress Rate 103
    3.2.5.4 Temperature 105

TABLE OF CONTENTS (Cont'd)

Page

3.0 ICE TECHNOLOGY (Cont'd)

3.2.6 Strength Properties of Low Salinity Ice 106
  3.2.6.1 Compressive Strength 106
  3.2.6.2 Tensile Strength 108
  3.2.6.3 Flexural Strength 109
  3.2.6.4 Fracture Toughness 110
3.2.7 Deformational and Shear Properties of Low and Non-Saline Ice 110
  3.2.7.1 Elastic Modulus 110
  3.2.7.2 Poission's Ratio 111
  3.2.7.3 Other Properties 111
3.2.8 Adhesion and Friction of Low and Non-Saline Ice 112
3.2.9 Unconsolidated and Reformed Ice 113

3.3 Regional Ice Characteristics 114
3.3.1 Beaufort Sea 114
3.3.2 Arctic Archipelago 116
3.3.3 Hudson Bay 116
3.3.4 Baffin Bay 117
3.3.5 Labrador Shelf 117
3.3.6 Grand Banks 119

3.4 Ice-Structure Interaction 120
3.4.1 Ice Effects at Various Stages of Development 120
  3.4.1.1 Final State Effects 120
  3.4.1.2 Construction Effects 122
  3.4.1.3 Operational Effects 122
  3.4.1.4 Factors in Ice Hazards 123

TABLE OF CONTENTS (Cont'd)

Page

3.0 ICE TECHNOLOGY (Cont'd)

- 3.4.2 Effect of Environmental Conditions of Interaction Forces 123
  - 3.4.2.1 Thermal Ice Forces 123
  - 3.4.2.2 Wind Forces 128
  - 3.4.2.3 Limited Drift Effect 131
  - 3.4.2.4 Limitations of Environment Conditions 133

- 3.4.3 Factors Generating Ice Interaction Pressures 133
  - 3.4.3.1 Main Load Factors 133
  - 3.4.3.2 Crushing Model 134
  - 3.4.3.3 Buckling of the Transmitting Media 175

- 3.5 Structural Response to Continuous Crushing 182
  - 3.5.1 Artificial islands 182
  - 3.5.2 Rigid Structures 185
  - 3.5.3 Flexible Structures 185

4.0 ARCTIC GEOTECHNIQUE 190

- 4.1 Geological Setting and Permafrost Distribution 190
  - 4.1.1 Physiographic Regions on Northern Coasts 190
  - 4.1.2 Genesis of Permafrost 193
  - 4.1.3 Permafrost Distribution 195
  - 4.1.4 Characteristics of Submarine Permafrost 195
  - 4.1.5 Seismicity 197

TABLE OF CONTENTS (Cont'd)

Page

4.0 ARCTIC GEOTECHNIQUE (Cont'd)

4.2 Site Studies 200
4.2.1 General Scope of Site Studies 200
4.2.2 Logistical Considerations for Field Work 203
4.2.3 Subsurface Exploration 203
4.2.3.1 General Scope of Subsurface Exploration 203
4.2.3.2 Drilling and Sampling Permafrost 204
4.2.3.3 Geophysical Surveys 205
4.2.3.4 In-situ Testing 205
4.2.3.5 In-situ Ground Temperature Measurements 205
4.2.4 Laboratory Testing of Frozen, Freezing and Thawing Soils 206

4.3 Foundation Design Considerations 207
4.3.1 General 207
4.3.2 Design Approach 208
4.3.3 Foundation Analyses 209
4.3.4 Geotechnical Considerations for Specific Structures 211

4.4 Earth Works 212
4.4.1 General 212
4.4.2 Borrow Material 213
4.4.3 Excavation 214
4.4.4 Compaction 215

TABLE OF CONTENTS (Cont'd)

Page

4.0 ARCTIC GEOTECHNIQUE (Cont'd)

4.5 Soil Improvement 216
  4.5.1 General 216
  4.5.2 Methods 216

4.6 Performance Monitoring 218
  4.6.1 General 218
  4.6.2 Temperatures 219
  4.6.3 Pore Water Pressure 219
  4.6.4 Vertical Deformation 219
  4.6.5 Horizontal Deformation 219
  4.6.6 Earth Loads 219

5.0 RESPONSES TO THE ICE ENVIRONMENT 221

5.1 Ice Attack on Structures 221
  5.1.1 Effects on Development 221

5.2 Alternative Solutions 225
  5.2.1 Ice Management 226
  5.2.2 Ice Resistant Structures 226
  5.2.3 Vessels 229
  5.2.4 Utilizing Ice 230
  5.2.5 Ice Control 231
  5.2.6 Avoiding Ice 233

TABLE OF CONTENTS (Cont'd)

Page

6.0 EXISTING REGULATIONS AND STANDARDS 235

6.1 Ice Aspects in Design Codes 235
  6.1.1 Canadian Standards Association 235
  6.1.2 American Association of State Highway and Transportation Officials 237
  6.1.3 USSR Standard SN76-66 238
  6.1.4 Det Norske Veritas: Rules for the Design, Construction and Inspection of Offshore Structures 238
  6.1.5 American Petroleum Institute: Recommended Practice RP 2A(1982) Planning, Designing and Constructing Fixed Offshore Platforms 238
  6.1.6 Other Codes and Standards 239

6.2 Geotechnical Aspects in Design Codes 239

6.3 Structural Codes and Standards 240
  6.3.1 Structural Steel 240
  6.3.2 Concrete Structures 241

6.4 Material Standards 242
  6.4.1 Structural Steel 242
  6.4.2 Reinforced and/or Prestressed Concrete 243

6.5 Quality Control Standards 248
  6.5.1 Structural Steel 248
  6.5.2 Structural Concrete 251

TABLE OF CONTENTS (Cont'd)

Page

6.0 EXISTING REGULATIONS AND STANDARDS (Cont'd)

6.6 Environmental Aspects 251
6.6.1 Land Use Regulations 251
6.6.2 Environmental Guidelines 252
6.6.2.1 Specific Environmental Conditions 252

7.0 DESIGN GUIDELINES 255

7.1 Functional Planning 255

7.2 Environmental Loads 257
7.2.1 Wave 257
7.2.2 Current 258
7.2.3 Wind 258
7.2.4 Ice 259
7.2.5 Seismic 261

7.3 Conceptual Design 262

7.4 Selection of Alternatives 263

7.5 Design Principles 264
7.5.1 Codes and Rules 264
7.5.1.1 Steel Structures 264
7.5.1.2 Concrete Structures 265

TABLE OF CONTENTS (Cont'd)

Page

7.0 DESIGN GUIDELINES (Cont'd)

- 7.5.2 Design Methodology 265
  - 7.5.2.1 Causeways or Breakwater Structures 266
  - 7.5.2.2 Piled Structures 277
  - 7.5.2.3 Gravity Structures 286
  - 7.5.2.4 Floating Structures 304
- 7.5.3 Fender Systems 311
  - 7.5.3.1 Energy Calculations 311
  - 7.5.3.2 Wharf Fender Types 313
- 7.5.4 Corrosion 314
  - 7.5.4.1 Corrosion Zones 314
  - 7.5.4.2 Anti-Corrosion Protection 315

8.0 CONSTRUCTION PROCEDURES AND TECHNIQUES 317

- 8.1 Construction Planning and Scheduling 317
- 8.2 Environmental Criteria 318
- 8.3 Construction Techniques 319
- 8.4 Material Selection 320
  - 8.4.1 On-site Materials 320
  - 8.4.2 Off-site Materials 321
- 8.5 Equipment Selection 322
- 8.6 Labour Supply 322

TABLE OF CONTENTS (Cont'd)

Page

8.0 CONSTRUCTION PROCEDURES AND TECHNIQUES (Cont'd)

8.7 Logistics 323
8.7.1 Transportation of Materials and Equipment to Site 325
8.7.2 Transportation of Personnel to Site 325
8.7.3 Local Transportation 326
8.7.4 Support System 327

8.8 Cost Control 328

8.9 Quality Control 328

9.0 EXISTING ARCTIC MARINE STRUCTURES 330

9.1 Wharf Structures 330

9.2 Oil/Gas Related Marine Structures 334

10.0 INFORMATION DEFICIENCIES AND RECOMMENDED RESEARCH AND DEVELOPMENT 336

10.1 Marine Environment 336
10.1.1 Structural Icing 336
10.1.2 Currents 336

10.2 Ice Technology 337

10.3 Geotechnical Research Topics in Submarine Permafrost 341

TABLE OF CONTENTS (Cont'd)

Page

10.0 INFORMATION DEFICIENCIES AND RECOMMENDED RESEARCH AND DEVELOPMENT (Cont'd)

10.4 Responses to Ice Environment 342
  10.4.1 Sea Ice Forces 342

10.5 Existing Regulations and Guidelines 344
  10.5.1 Environmental Policy 344
  10.5.2 Labour Codes 344

10.6 Design and Construction 344

LIST OF ILLUSTRATIONS

LIST OF FIGURES

		Page No.
Figure 1.1	Geographical Location of Canadian Offshore Oil and Gas Reserves	2
Figure 1.2	Duration of Daylight (Hours)	6
Figure 1.3	Trends in Ship Sizes	9
Figure 1.4	Logic for Planning and Design	17
Figure 2.1	Mean Air Temperature for January	20
Figure 2.2	Mean Air Temperature for July	23
Figure 2.3	Wind-Chill Nomogram	24
Figure 2.4	Mean Total Precipitation for January	26
Figure 2.5	Mean Total Precipitation for July	27
Figure 2.6	Dates of First and last Snow Cover	28
Figure 2.7	Mean Sea Level Pressure - (mb) (January 1931-1960)	32
Figure 2.8	Mean Sea Level Pressure - (mb) (July 1931-1960)	32
Figure 2.9	Direction Frequencies of January Winds	33
Figure 2.10	Direction Frequencies of July Winds	33
Figure 2.11	Principal Arctic Storm Tracks	41
Figure 2.12	Duration of Daylight Relative to Latitude	43
Figure 2.13	Icing Diagram (from Mertins, 1968)	51
Figure 3.1	Continuous Molecular Structure of Ice	71
Figure 3.2	Preferred Growth of Crystals (from Percy and Pounder, 1958)	74
Figure 3.3	Variation of Freezing Point and Inversion Temperature with Salinity	75
Figure 3.4	Idealized Diagram of the Shape of Brine Inclusion in Sea Ice	76

LIST OF FIGURES (Cont'd)

		Page No.
Figure 3.5	Brine Migration along the Temperature Gradient	76
Figure 3.6	Ice Failure Mode in Rubble Field Formation	78
Figure 3.7	Typical Stress-Strain Diagrams for Salt Water Ice Specimens in Uniaxial Compression (from Wang, 1981)	82
Figure 3.8	Influence of Temperature on Salt Water Ice Strength (Michel, 1978)	89
Figure 3.9	Summary of Data for σ_C as Function of Brine Porosity	91
Figure 3.10	Variation of σ_C with Strain Rate in Columnar Sea Ice at -10°C	92
Figure 3.11	Variation of σ_C with Strain Rate in Granular Ice at -10°C	92
Figure 3.12	Variation of σ_C with Temperature for three Ice Types	93
Figure 3.13	Variation of Uniaxial Tensile Strength with Temperature and Salinity for Sea Ice (A) Vertical Specimens (B) Horizontal Specimens	94
Figure 3.14	Summary of Data for σ_{Ft} as a Function of Brine Porosity	95
Figure 3.15	Rate-Dependent Plane Strain Fracture Toughness K_{IC} for Sea Ice (from Urabe and Yoshitabe, 1981)	96
Figure 3.16	Variation of K_{IC} with Temperature and Loading Rate (from Miller, 1979).	97
Figure 3.17	Elastic Modulus of Cold Arctic Sea Ice (Langleben and Pounder, 1963)	98
Figure 3.18	Adhesion Strength τ_B for various materials	98
Figure 3.19	Adhesion Strength as a Function of the Brine Volume	100
Figure 3.20	Static and Kinematic Friction Coefficients for Ice (from Saeki, et. al. 1979)	101

LIST OF FIGURES (Cont'd) Page No.

Figure 3.21 Average Multi-Year Salinity Profiles 103

Figure 3.22 Effect of Strain Rate on Yield Strength 104

Figure 3.23 Stress/Strain Rate Relations for Creep of Glacier Ice 104

Figure 3.24 Compressive Strength of Low Salinity Ice as a Function of Temperature 105

Figure 3.25 Tensile Strength of Low Salinity Ice as a Function of Temperature 106

Figure 3.26 Summary of Data on the Strength of Non-Saline Ice and Snow (from Weeks and Mellor, 1983) 107

Figure 3.27 Effect of Strain Rate on compressive and Tensile Strength for Fine-Grained Non-Saline Ice 108

Figure 3.28 Average Values of Flexural Strength of Lake Ice as Determined from Tests on in-place cantilever and simply supported Beams 109

Figure 3.29 Summary of Young's Modulus Data for Non-Saline Ice and Snow 111

Figure 3.30 Winter Ice Zones of Southern Beaufort Sea (from Kovacs & Mellor, 1974) 114

Figure 3.31(A) Icebergs. Sightings over the Grand Banks over a 9 year period. 119

Figure 3.31(B) Grand Banks - General Surface Circulation and Iceberg Limits 121

Figure 3.32 Sequential Breakdown of Edge of Ice Sheet 143

Figure 3.33 Force - Deformation Diagram 146

Figure 3.34 Probability Distribution 148

Figure 3.35 Probability Density for One Channel 148

Figure 3.36 Probability Density for Instantaneous Pressure 149

LIST OF FIGURES (Cont'd) Page No.

Figure 3.37 Exceedance Probabilities of Instantaneous Pressure for Cold Sea Ice 150

Figure 3.38 Definition Sketch 151

Figure 3.39 Initial interaction Between Ice and Sloping Structure 152

Figure 3.40 General Interaction Between Ice and Sloping Structure 153

Figure 3.41 C_1 Versus Slope Angle and Friction 155

Figure 3.42 C_2 Versus Slope Angle and Friction 155

Figure 3.43 Horizontal Force Versus Slope Angle and Friction (Simple 2-D Theory) 156

Figure 3.44 Effect of Ice Strength on Horizontal Force (Simple 2-D Theory) 156

Figure 3.45 Horizontal Force Versus Ice Thickness (Simple 2-D Theory) 157

Figure 3.46 Ice Action on Sloping Structures 158

Figure 3.47 Ice Force Coefficients for Plastic Analysis (Ralston, 1977) 160

Figure 3.48 Ridge Failure on Cone 161

Figure 3.49 Simple Interaction Model of Unconsolidated Ridge 162

Figure 3.50 Adfreeze Bond Failure 164

Figure 3.51 Simple Ice Ride-Up 165

Figure 3.52 Forces for Simple Ride Up 166

Figure 3.53 Kinematic Instability for Pile Up at Top of Slope 168

Figure 3.54 Criterion for Ride-Up Past a change in Slope 170

Figure 3.55 Compression Instability 170

LIST OF FIGURES (Cont'd) Page No.

Figure 3.56	Potential Jamming of First Ice Block at Change of Slope Angle	171
Figure 3.57	Force (or Pressure) Versus Displacement from Identation Tests	172
Figure 3.58	A Probabilistic Model of Non-Simultaneous Occurrence of Peak Pressure	173
Figure 3.59	Predicted Effective Ice Pressure and Suggested Design Curve	174
Figure 3.60	CDF of Peak Indentation Pressure for Tests at High Strain Rate and Warm Temperature	174
Figure 3.61	Geometry of a Beam with a Rectangular Cross-section resting on an Elastic Foundation with Compressive Axial Load P	175
Figure 3.62	Lower Envelope Plots of Non-Dimensional Buckling Pressure (P/BKL_b^2) with respect to the Ratio of Length to Characteristic Length (L/L_b)	176
Figure 3.63	Plots of the Lowest Buckling Pressure (P/KLp^2) with respect to (R/Lp) for an Infinite Ice Sheet Stressed Uniformly along the Periphery of an Internal Hole (From Takagi, 1978)	176
Figure 3.64	Geometry of Semi-Infinite Ice Sheet Acted on By a Uniformly Distributed Load Over a Finite Length	178
Figure 3.65	Geometry of a Semi-Infinite Floating Ice Sheet Moving against a Rigid Cylindrical Structure	178
Figure 3.66	Geometry of a semi-Infinite Wedge-Shaped Floating Ice Sheet	178
Figure 3.67	Plots of Non-Dimensional Buckling Pressure ($P/2RKLp^2$) with respect to (2R/Lp) for semi-infinite wedge-shaped ice sheets	177
Figure 3.68	Plots of Non-dimensional Buckling pressure ($P/BKLp^3$) with Respect to (R/Lp) for Semi-infinite Wedge-Shaped Ice Sheets	179

LIST OF FIGURES (Cont'd) Page No.

Figure 3.69	Plots of Concentrated Buckling Force (P/KLp^3) with Respect to the Taper Angle of Semi-infinite Wedge-shaped Ice Sheets	180
Figure 3.70	Plots of Buckling Pressure ($P/2RKLp^2$) with Respect to ($2R/Lp$) when Wedged-Angle α is greater than π and when P creates a compressive as well as tensile stress field	180
Figure 3.71	Plots of Buckling Pressure ($P/2RKLp^2$) with Respect to ($2R/Lp$) when wedge-angle α is greater than π and when P creates only a tensile stress field	181
Figure 3.72	Single Shaft Analysis Ice Force and Waterline Displacement Development of a Limit Cycle	187
Figure 3.73	Bridge Pier Analysis - Foundation Reaction for Varying Strain Rates	188
Figure 3.74	Light House Analysis - Ice Force and Reaction for High Value of Ice Stiffness with Variation of Strain Rate	189
Figure 4.1	Physiographic Regions in Northern Canada	191
Figure 4.2	Relationship between Sea Level Rise and Geoisostatic Rebound	194
Figure 4.3	Distribution of Permafrost in Canada	196
Figure 4.4	New Acceleration Seismic Zoning Map of Northern Canada (from Heidebrecht et. al. 1983)	198
Figure 4.5	New Velocity Seismic Zoning Map of Northern Canada (from Heidebrecht et. al. 1983)	199
Figure 4.6	Site Study Phases and Data Sources	201
Figure 4.7	Design Approach for Arctic Dock Structures (Modified after Johnston, 1981)	210
Figure 5.1	Various Modes of Ice Attack on Offshore or Coastal Structure	222
Figure 5.2	Alternative Schemes capable of Handling Ice and their Operational Consequences	227

LIST OF FIGURES (Cont'd)

		Page No.
Figure 5.3	Photograph - Caisson Retained Ice Resistant Island Forming Rubble Field and Reducing Direct Ice-Island Impact Forces	229
Figure 5.4	Photograph - Extensive Use of Ice Roads in the Beaufort Sea Arctic Islands for Transporting Equipment and Constructing Artificial Islands	230
Figure 5.5	Photograph - Two Vessel Directing an Iceberg away from a Drilling Platform.	232
Figure 5.6	Photograph - Protective Barrier of Ice and Gravel Built around a Natural Gas Pipeline to prevent the Effects of Ice Scour	234
Figure 7.1	Schematic Diagram of Large Loads imposed on a Piling bent with Diagonal Bracing. The failure occurred with ice mass thawed free from Piling during low tide	278
Figure 7.2	Schematic of a Second Type Failure Ice on Diagonal Brace acted as a bead on string, slipping down member with sufficient velocity to exert tremendous force as shown.	278
Figure 7.3	Crushing type of ice failure with a clean slot being cut which is nearly the diameter of the pile	280
Figure 7.4	Afanas'ev Curve - to compute the magnitude of lateral ice load	280
Figure 7.5	Compressive strength of Granular sea ice as a function of strain rate (Exxon 1974)	282
Figure 7.6	Oscillating Force on a Structure	283
Figure 7.7	Response Spectra	285
Figure 7.8	Interaction of Ice Sheet with wide structure	287
Figure 7.9	Applied Pressure and Elastic Limit Versus E	288
Figure 7.10	Stability Analysis: Forces on Moving Body of Earth	292

LIST OF FIGURES (Cont'd)

		Page No.
Figure 7.11	Graph of H/V for $\mu = 0.15$ and 0.20 for various values of cone angle α	293
Figure 7.12	Plan View of an ice sheet being failed in Bending. First the radial cracks form and then the sheet fails totally with the formation of the circumferential cracks	294
Figure 7.13	Ice Sheet Failure against a conical structure: Dimensionless coefficients (A_1, A_2, A_3, and A_4) for Plastic Analysis	295
Figure 7.14	Ice Sheet Failure against a conical structure: Dimensionless coefficients (B_1 and B_2) for Plastic Analysis	296
Figure 7.15	Instability Modes to be considered in cassion design (a) Gobal Truncation (b) Local Passive Failure (c) Tensile Ice Breakout Load with active soil pressure (d) Rotational Instability in Plan	299
Figure 7.16	Iceberg Impact on Cylindrical Structure	303
Figure 7.17	Iceberg Impact on Conical Structure	303
Figure 7.18	Potential Failure Planes/Modes for Causeway	301
Figure 7.19	Typical Ice Boom	305
Figure 7.20	Graph - To Compute Thermal Ice Pressure	309
Figure 7.21	Graph - To Compute wind induced ice pressure	310
Figure 7.22	Graph - To Compute approach velocity	312

LIST OF TABLES

		Page No.
Table 1.1	Summary of Total Potential Offshore Oil and Gas Resources in Canada - 1983	3
Table 1.2	Comparison of Offshore and Coastal Marine Structure	13
Table 2.1	Mean Daily Temperatures	21
Table 2.2	Percentage Frequency of Occurrence of Precipitation Types	29
Table 2.3	Maximum Observed Hourly Wind Speed and Direction	34
Table 2.4	Average Number of Hours of Strong Winds	35
Table 2.5	Average Number of Days with Gales	36
Table 2.6	Average Number of Days with Fog	45
Table 2.7	Wind Speed and Surface visibility at Resolute, N.W.T.	46
Table 2.8	Return Period of the Maximum Amount of ice that would accumulate in one storm	48
Table 2.9	List of catalogues available from IOS Sidney, B.C.	53
Table 3.1	Ice Cover Classification (from Michel, 1975)	73
Table 3.2	Friction Coefficients (from Frederking, 1983)	112
Table 3.3	Measured Adhesion Strength of some materials to Ice (from Frederking, 1983)	113
Table 3.4	Factors in Engineering Design for Ice Hazards	124
Table 3.5	Logic Illustration to assess severity of Ice Forces at a Specific Site and Structure	126
Table 3.6	Thermal Ice Forces Based on Ice Thickness	127
Table 3.7	Factors Generating Ice Interaction Pressures	135

LIST OF TABLES Cont'd) Page No.

Table 3.8	Comparison of Effective Pressures for Vertical Piles and Piers	142
Table 3.9	Algorithm for Energy-Balance Ice Impact Computations	189
Table 4.1	Granular Deposits Prevalent in Northern Canadian Physiographic Regions	213
Table 5.1	Average Properties of Cold Sea Ice	223
Table 5.2	Existing and Proposed Ice Management Techniques in the Canadian Arctic	228
Table 6.1	Pier Coefficients	237
Table 6.2	Water-Cement Ratios and Compressive Strengths for three exposure zones	245
Table 7.1	Logic Diagram for the preparation of detailed design of Arctic Marine structures	256
Table 7.2	Perspective: Planning consideration for Rubble Mound Structure in Cold Regions	267
Table 7.3	Focus: Design Factors for Rubble Mound Structures in Cold Regions	268

ARCTIC MARINE DESIGN AND CONSTRUCTION HANDBOOK
VOLUME 2
ANNOTATED BIBLIOGRAPHY
TABLE OF CONTENTS

Page No.

SUBJECT

1.0 Ice Technology
  1.1 Type, Structure and Morphological Properties 1-57
  1.2 Ice Structure Interaction 58-146
  1.3 Ice Structure Interaction, Moving Vessels 147-156
  1.4 Ice Scour 157-169

2.0 Arctic Geotechnique 170-221

3.0 Responses to the Ice Environment
  3.1 Utilizing Ice 222-240
  3.2 Ice-Resistant Schemes 241-247
  3.3 Ice Control 248-252

4.0 Existing Regulations and Guidelines 253-264

5.0 Design Guidelines 265-307

6.0 Construction Procedures and Techniques 308-323

7.0 Case Histories 324-325

8.0 Instrumentation and Monitoring 326-330

APPENDICES

Sources of Information on the Arctic

APPENDIX 1 - List of Agencies and Organization 331-335

APPENDIX 2 - List of Useful References 336-353

APPENDIX 3 - List of Conferences 354

APPENXIX 4 - List of Companies Providing Sealift Transportation in the Canadian Arctic 355-359

CHAPTER 1

INTRODUCTION

1. INTRODUCTION

1.1 Arctic Opportunities

Arctic regions have been the scene of extensive exploration activity during the past several decades. The Arctic contains a very substantial portion of Canada's natural resources and the push for development is expected to continue. This development will require construction, maintenance and operation of ports, harbours and navigational aids. Offshore and shoreline production facilities and transport terminals will have to be developed to enable these resources to reach international markets. This handbook deals primarily with civil engineering structures required for port and harbour facilities in the Canadian Arctic.

1.1.1 Resources in the Arctic

Exploration has shown that the Arctic offers substantial reserves of zinc, lead, asbestos, silver and gold. Attractive metal prices in recent years has encouraged an expansion of exploration resulting in the development of large-scale operations such as Canadian Tungsten on Baffin Island, Cominco on Little Cornwallis Island, and Asbestos Corporation on the Hudson Strait.

By far the most concentrated efforts in the search for natural resources during the past decade and a half have been directed towards the estimation and development of oil and gas reserves in the Arctic, Subarctic and east coast regions. Present exploration results indicate that a substantial amount of Canadian oil and gas reserves are in the Arctic and Subarctic regions.

1.1.2 Oil and Gas in Ice Affected Areas

Major oil and gas finds are located in the Canadian offshore regions. Most of these offshore finds are located in regions which are affected by the presence of ice, in one form or another, for at least part of the year. The geographical location of Canadian offshore oil and gas reserves is presented in Figure 1.1. It is estimated that the ultimate recoverable petroleum potential in these regions yields about 60 percent of total Canadian reserves. Table 1.1 shows the distribution of resources in accordance with the estimate in 1983 by the Geological Survey of Canada.

In addition to the ice-affected offshore areas, oil and gas reserves are located in the West Coast offshore region including Queen Charlotte Islands which is not affected by ice; on the Scotia Shelf and Georges Bank including Sable Island where ice does not play a major role and in the Gulf of St. Lawrence region where mixed sea ice and river ice effects are present.

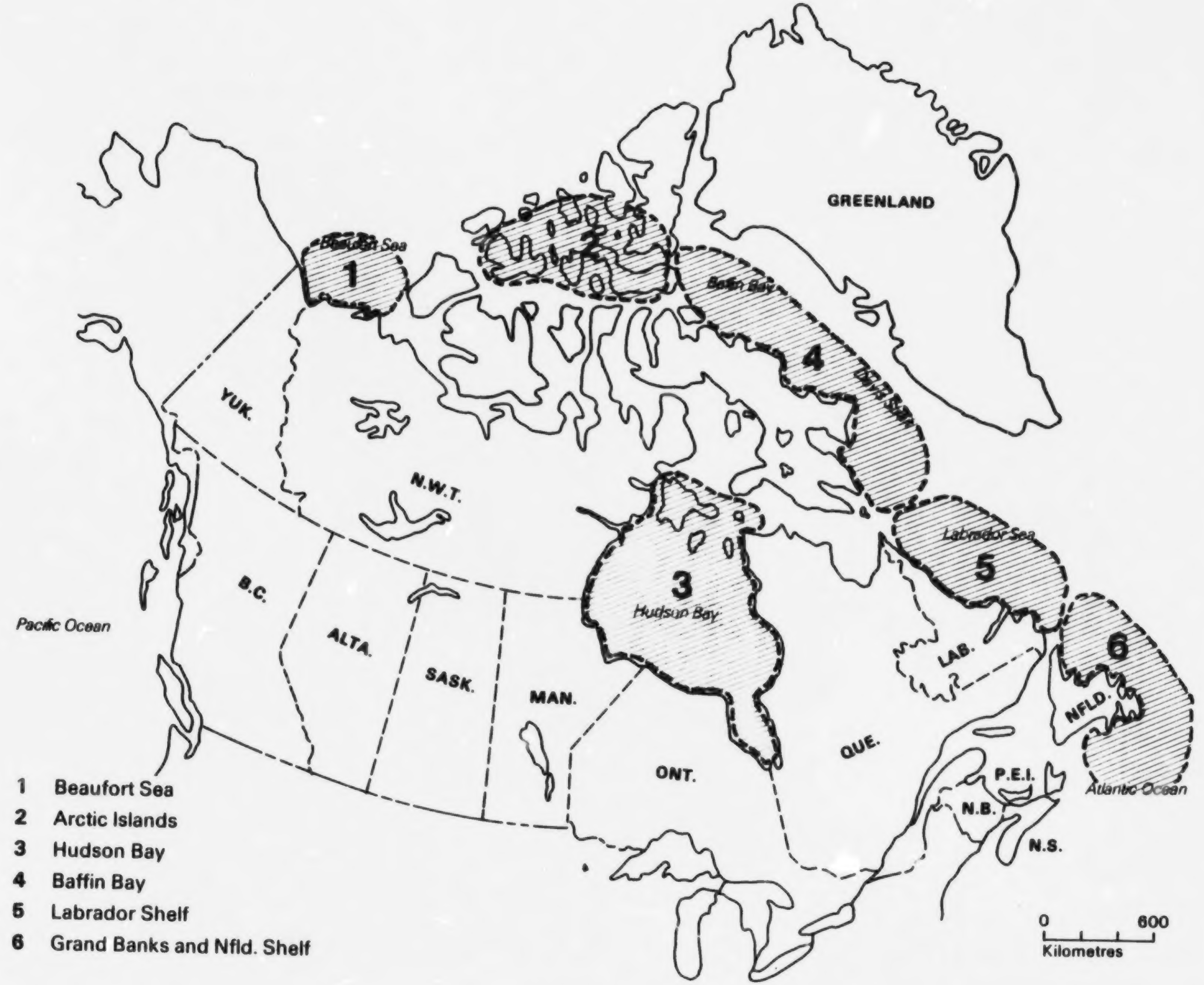

GREENLAND
Beaufort Sea
1
Baffin Bay
4
Labrador Sea
5
6
3
Hudson Bay
YUK.
N.W.T.
B.C.
ALTA.
SASK.
MAN.
ONT.
QUE.
LAB.
NFLD.
P.E.I.
N.B.
N.S.
Pacific Ocean
Atlantic Ocean
0
600
Kilometres
1 Beaufort Sea
2 Arctic Islands
3 Hudson Bay
4 Baffin Bay
5 Labrador Shelf
6 Grand Banks and Nfld. Shelf

Figure 1.1 Geographical Locations of Canadian Offshore Oil and Gas Reserves

Table 1.1 Summary of Total Potential Offshore Oil and Gas Resources in Canada – 1983

Region	Average Expectation Oil 10^6 m^3	Average Expectation Gas 10^9 m^3
Beaufort Sea and Mackenzie Delta (Offshore)	1271°	1721°
Arctic Islands (Sverdrup Basin, Fold Belt and Arctic Stable Platform)	686*	2257*
Hudson Bay and Northern Lowlands	130*	90*
Baffin Bay	55	270
Labrador Shelf	134	745
Newfoundland and Grand Banks Shelf and Basin including Hibernia	1448	750
Total (Ice-Affected Waters)	3724	5833
Total (Canada)	5893	12522
Percent of Canadian Total in Ice Affected Waters	63%	46.5%

o From Discussions with Geological Survey of Canada

* Total Value Includes a Minor Percentage Onshore

Oil and gas exploration has been intensive in the Arctic, especially in the Mackenzie Delta, Beaufort Sea and land and offshore zones of the Arctic Islands. For example, Panarctic Oils Ltd. has drilled 26 offshore wells during the past 10 years. The Beaufort areas have had 4 holes indicating oil, and 5 holes indicating gas, and 5 holes indicating oil and gas. From a total drilling program carried on in the arctic ice, confirmed gas and oil reserves in the Canadian arctic including the Arctic Islands and Beaufort Sea, are now 645.1 10^9 m^3 and 193.3 10^6 m^3 respectively (COGLA, 1983). These exploration successes have initiated the development of gas transportation mechanisms and corridors from the Arctic.

Extensive oil and gas discoveries, particularly in the Sable Island field and at the ice-affected Hibernia structure, off the Canadian East Coast, have reached a point where the construction of the first Canadian large-scale offshore production facility and underwater pipeline transportation system is a few years from initiation. These developments warrant the installation of an infrastructure for sea transport in the described regions in the next decades.

1.2 Pertinent Canadian Arctic Regions

The Canadian Arctic and Sub-Arctic regions are generally identified on the basis of ice variations and physiographic features as noted. noted.

1.2.1 Regions based on Ice Variations

The Arctic and Subarctic offshore oil and gas reserve areas have been separated into six regional zones as a result of distinctly varying ice conditions. These zones include the Beaufort Sea, Arctic Islands, Hudson Bay, Baffin Bay, Labrador Shelf and Grand Banks. Figure 1.1.

Generally, the Beaufort Sea is characterized by three distinct ice zones; landfast ice, transition and polar pack whereas the Arctic Islands are comprised of a mixture of multi-year and first-year ice. Hudson Bay is completely covered by an annual sea ice layer while Baffin Bay is known for icebergs and multi-year floes. The Labrador Shelf consists of primarily first-year ice, however, multi-year floes and icebergs are known to drift south from Baffin Bay. The Grand Banks experience storm conditions which prevent the development of an ice cover in winter, however, icebergs and pack ice drifting south from Baffin Bay present a potential major problem.

1.2.2 Physiographic Regions

The northern coast of Canada is extremely extensive and variable. It ranges from steep mountain faces which rise directly from deep sea coastal areas to flat, gently sloping coastlines with extensive beaches of glacio-fluvial deposits which extend miles outward into shallow seas.

The northern territories have been divided into seven physiographic regions. They include:

- Arctic Coastal Plain
- Interior Plains
- Arctic Lowlands
- Innuitian Regions
- Davis Region
- Hudson Region
- Canadian Shield

Individual physiographic regional characteristics are discussed in Chapter 4 of this handbook.

1.2.3 General Climate

As shown on the enclosed Figure 1.2 and as described in Chapter 2, the arctic has prolonged periods of darkness. During daylight periods the effects of blizzards also result in periods of low visibility.

In addition to the effects of darkness and blizzards, there are problems of "white-out" which comes from the shadowless illumination of the white plains. Ground operations are hampered and aircraft must resort to instrument flying.

Fog is a major concern during the summer months when substantial open water areas are present. At this time, fog may drift over the area, imposing severe limitations upon navigation by sea and air.

The high Arctic has low temperatures and long periods of severe frost. The mean annual temperature at the North Pole is about -23°C. In Canada's most northerly land areas, temperatures can remain below -36°C for half of the time during the coldest three winter months. Summer in the Arctic, although short, is quite tolerable with temperatures reaching several degrees above freezing in most places.

A special feature of the Canadian Arctic, as compared to the calm of Siberia, arises from winds creating windchill factors.

The frozen Arctic Ocean supplies little moisture for precipitation. Generally, the total snow cover ranges from about 50 cm in the Mackenzie Bay region to about 23 cm in the Arctic Ocean. The insulating properties of snow cover influence ice formation and hence the ice thickness in a particular region. Snow drifts accumulate in any natural or unnatural recess in the topography and cause problems. During the Arctic summer, the snow melts on most of the archipelago islands, except for some areas of glacial activity in the western archipelago.

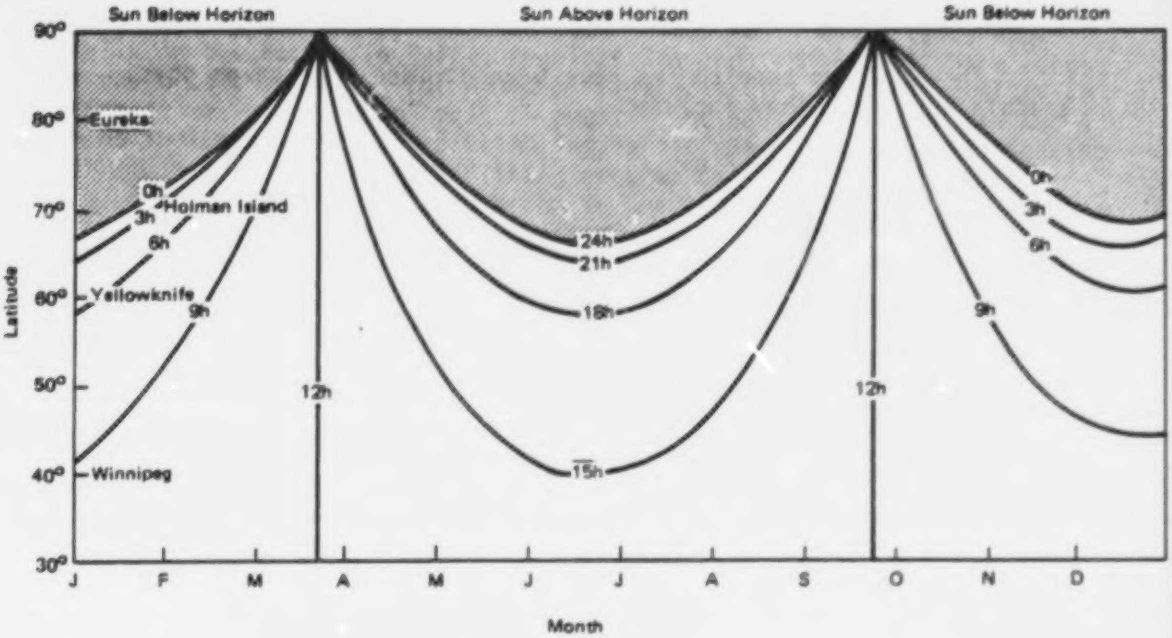


Figure 1.2 Duration of Daylight (Hours) (After Burns, 1973)

Ellesmere Island, the source of most ice islands in the western archipelago, has such activity and is snow-covered the entire year.

The main challenge to living and working in the Arctic are long periods of cold and darkness. The main obstacles to construction and operation arise from the combination of ice and permanently frozen ground.

1.3 Functional Requirements

The functional requirements of arctic marine structures are directly related to type of cargo and type of vessel which must be serviced by the terminal.

The type of cargo and rate of handling required determines the landside features of terminal interface. Each material to be handled has its own characteristics which must be carefully considered in the context of the site specific Arctic environmental conditions. Material handling systems at arctic terminals have mostly been "modified versions" from southern terminals. These are not necessarily suitable to the harsh arctic environment. The selection and installation of these systems requires special study and is beyond the scope of this handbook.

The type of vessel using a terminal directly affects marine structural features. The vessel characteristics will be determined by the terminal operational requirements. The major elements being amount and type of cargo to be handled per year, duration of navigational season and shipping risk factors which relate vessel characteristics to arctic environmental factors en route and at the site.

1.3.1 Vessel Characteristics

Depending upon terminal site location, the vessel characteristics may or may not be significantly different from those serving non-arctic terminals. It is essential when locating and designing the marine structures portion of the terminal, to be informed with respect to vessel operating characteristics.

These characteristics will significantly influence site selection, wharf orientation, type of berthing structure and duration of navigation season. Superimposed upon vessel characteristics will be site environmental factors which must be taken into consideration by the designer and constructor of arctic marine facilities.

For planning purposes the types of vessels that may have either a direct or indirect effect on the design of port facilities are:

- Container Ships
- Tankers
- Dry Bulk Carriers
- General Cargo Ships
- Ro-Ro Ships
- Combo Vessels
- Barge Carriers
- Liquified Gas Carriers
- Offshore Service Vessels

An indication of trends in ship sizes and vessel characteristics are presented in Figure 1.3 for the first four types of ships. For specific vessel information refer to the Lloyds Register for Vessels.

1.3.2 Marine Terminal Components

The primary purpose of a marine terminal is to provide basic port facilities and services to safely and effectively berth and secure vessels, service them, load and/or discharge cargo, store and/or recover cargo, and provide infrastructure facilities for terminal operating personnel. Major civil engineering features of a port which may be affected by the arctic environment are as follows:

- **Harbour Area**

  Generally, a protected area for vessels against severe wave and/or ice action. This area may be available through natural geographic features or by man-made structures. If a protected area is formed by new structures such as breakwaters, it will be essential to assess the impact on natural site environmental conditions. Of particular significance will be the effect on future ice regime in the harbour area. All other environmental aspects usually analysed in planning artifical harbours must be taken into consideration.

- **Breakwaters**

  Where sea-state conditions require breakwaters, their effect upon ice conditions, currents, litoral drift and wave climate must be assessed. In the design of breakwater structures, the effect of ice action on the structure, in many cases is the most significant environmental element.

- **Stationary Icebreakers**

  In order to provide year round operation in ports that are subject to severe ice conditions, stationary icebreakers in the form of icebreaker cells may be installed to protect moored vessels from large ice-floes. The purpose of the icebreaker cells is to deflect and/or break up ice-floes and reduce them to a sufficiently small size so as not to endanger a moored vessel. The icebreaker cells are usually gravity type structures filled with quarry-run rock or gravel. An example of the utilization of stationary icebreakers may be observed at the Golden Eagle Oil Terminal Wharf at Hadlow Cove, Quebec (Volume 2, Page 296).

- **Shore Protection**

  The exposed shoreline of the coastal facilities must be adequately protected against erosion and deterioration from waves and ice action. Particular attention is required if the terminal construction has modified the wave or current climate or the ice regime at the site.

  An example of problems related to shore erosion and protection required is covered in a March 1981 report by Public Works Canada, entitled "Evaluation and Recommendations on Tuktoyaktuk Shore Protection Works" (Refer to Volume 2, Page 219).

- **Wharf Structures**

  The wharf structure is the prime physical element providing the interface between the vessel and terminal. The structure must

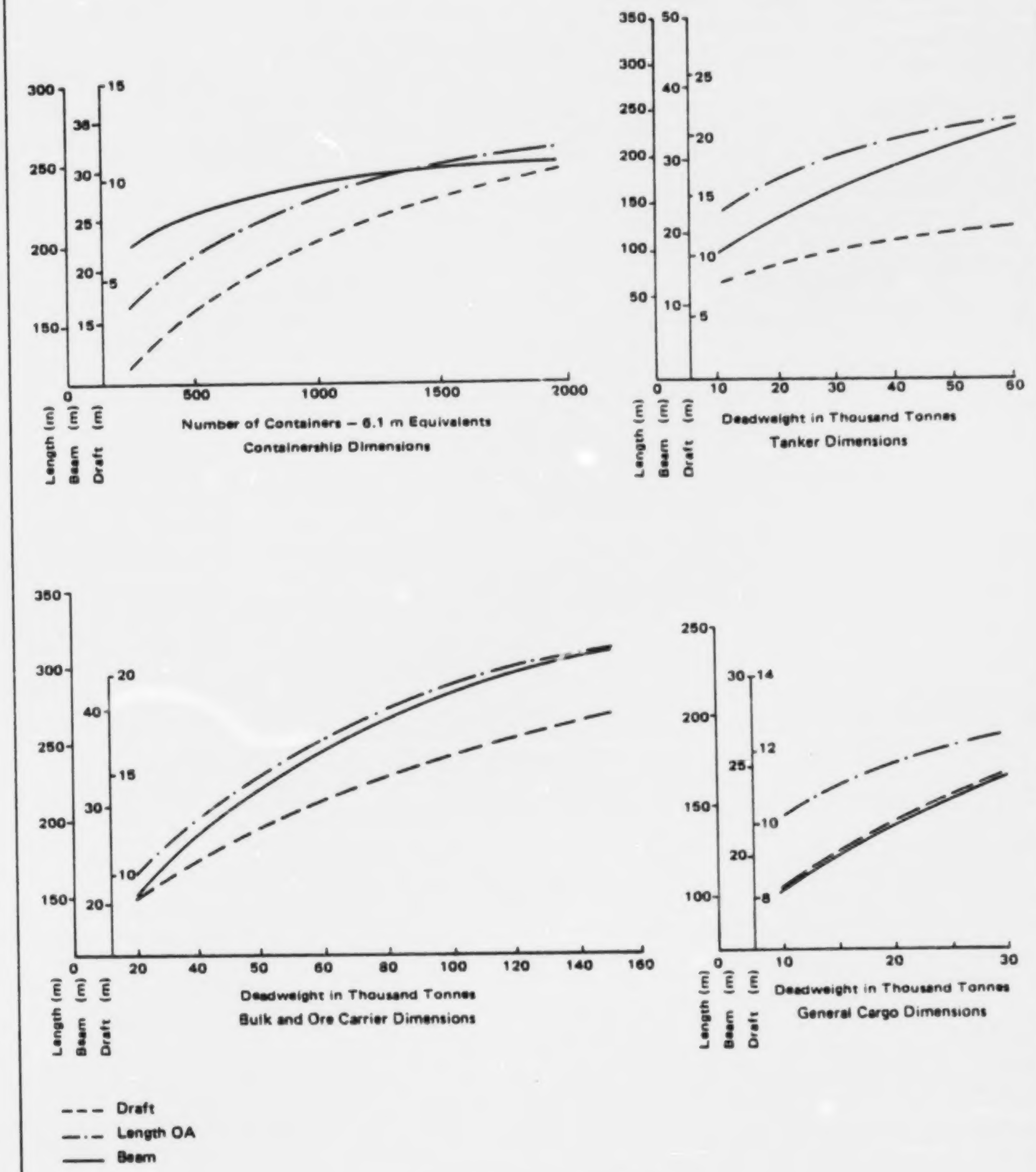


Figure 1.3 Trends in Ship Sizes

permit a safe approach, berthing and departure of the vessel, operating in the site specific environmental conditions of the terminal. Siting of wharf structures in the Arctic is critical to operational feasibility. In the past, some Arctic port facilities have been provided without adequate consideration being given to navigational factors. The four key elements which must be considered in locating an arctic wharf structure are:

1) Navigational aspects
2) Structural design
3) Construction factors
4) Operational feasibility.

The Arctic environment greatly influences and to a large degree controls the type of wharf structure which may be utilized. A risk analysis is often required to relate structural susceptibility to environmental damage to a cost/benefit comparison for reliability of terminal operation.

Fendering is provided at the berthing face to absorb the impact of berthing vessels. In the Arctic, these forces may be intensified by environmental conditions peculiar to the specific site.

The wharf fender systems are particularly susceptible to ice damage and in some cases, practice has been to install fender systems which can be removed during periods of adverse ice conditions. An example is the pneumatic floating fenders utilized at Deception Bay and Hadlow Cove terminals (Volume 2, Page 297).

Normally, the berthing structure deck provides the foundation support for loading or unloading cargo systems and services such as water, power and fuel. In the case of oil terminals, additional provisions such as disposal of bilge-wash will be required. In the Arctic, the severity of environmental conditions demands careful attention be given to the design of these portions of the wharf structure.

For material handling systems and related assessment procedures refer to Termpol Code Canadian Coast Guard.

- Mooring Facilities

The vessel must be securely and safely moored at berth against wind, currents, waves and ice forces. To accomplish this effectively, mooring lines should be arranged in a definite pattern fore, aft and athwartship to distribute the mooring forces to the terminal structure or to the mooring dolphins. Bollards or motorized capstans are normally provided on the terminal structure and mooring dolphins to receive the ship's lines. Access to mooring dolphins and security for operating personnel require special attention for arctic terminals.

- Navigational Aids

Navigation aids are required to guide the ship to a safe passage from entrance to exit. These aids are important to prevent the vessel from grounding and collision. The navigation aids generally take the form of navigation lights, marker buoys, Doppler docking aid (radar or sonar) capable of transmitting both the speed and direction of a docking vessel to a control room. Current and wave meters are now recognized as useful aids in improving the security of vessels approaching and departing from isolated terminal facilities.

The provision of navigational aids is the responsibility of Coast Guard Canada and it is mandatory to consult this agency for harbour development projects in Canada.

1.4 Types of Structures

Marine structures built in ice-affected waters must be designed to withstand all forces due to ice action. Depending on the location, ice forces may exceed other environmental and operational forces by several magnitudes.

There are three major types of marine structures, namely: bottom founded structures, floating mooring systems and subsea connections. Each type has its advantages and disadvantages, depending on the ice conditions, water depth and other environmental factors. A list of marine type facilities and their particular ice interaction features is given in Table 1.2. Offshore mooring systems and coastal schemes are shown.

A number of marine structures placed in ice affected waters have performed well over a period of several years. Steel structures such as piled wharves, jacket, jack-up and monopods have been used in Cook Inlet, Alaska, with its moderate ice conditions, as early as 1963. Initially, ice action caused considerable operational and structural problems. These, however, were overcome with an increased knowledge of ice and its interaction with the structure. Steel sheet pile cells form the structural system for marine terminals at Deception Bay (Volume 2, Page 297) and at Nanisivik (Volume 2, Page 315). Gravel islands have proven their suitability in the southern Beaufort Sea to withstand severe ice conditions. (Report by Dome Petroleum Limited, Esso Resources Canada and Gulf Canada Resources Inc. - Vol. 2, Appendix 2).

1.4.1 Bottom Founded Marine Structures

Port facilities in arctic ice covered waters require the design and construction of structures which can either withstand or avoid the extreme forces imposed by the ice at the selected site.

1.4.1.1 Unconfined Fill Islands

Although these structures are primarily related to oil and gas exploration and production systems, their performance is of interest to port engineers. Unconfined fill islands have been used to drill exploratory wells in the shallow waters of the Beaufort Sea since 1972. At least thirty of these islands have been built in water depths ranging from 1 to 14 m. Construction materials have included sand, silt and gravel and construction techniques have varied widely. The islands take the form of sacrificial beach islands or earth berm islands.

The first island built, Immerk B-48, utilized "conventional" or "protected fill" construction techniques. This involved protection of the slope from wave and ice action using filter cloth, chain link fencing, submarine netting, sand filled plastic tubes, sand bags or gabions filled with sand bags. As well as protecting the slopes of the island from wave erosion these protection measures allow steeper slopes and hence a lower total volume of fill for the required island area. Depending on the protection material, fill material and wave regime, slopes may range from 1:2 for heavily protected areas to 1:20 for very lightly protected areas. A common design has been sandbag protection with slopes 1:2 or 1:3.5 for gravel islands.

A second type of protection is the "sacrificial beach" island which utilizes a wide beach (about 20-300 m) designed to slowly erode with wave action. This type of island does not require any additional protection, but involves a large volume of fill material as the slope at the edge of the sacrificial beach is usually about 1:50. Some of the first islands built utilized commonly available silt as a construction material. The consolidation process for silt is very slow and silt islands to date have only been usable when frozen in the winter months. They may be more suitable as ice breakers and break waters.

Unconfined earth islands have been built in the summer using gravel barges and in the winter using gravel trucks on the ice surface. They are usable year round and even though present islands have been designed as temporary drilling platforms their performance seems to indicate they could easily be designed for use as breakwaters, ice breakers and access causeways to mooring facilities.

1.4.1.2 Confined Fill Structures

Cellular sheet pile wharves have been built at Deception Bay (Saunders 1975 - Vol. 2, Page 297) and Nanisivik (Girgrah and Shah 1977 - Vol. 2, Page 315). The Nanisivik dock consists of three circular cells of steel interlocking piles driven into the seabed and filled with

TYPES OF ARCTIC MARINE STRUCTURES	ADVANTAGES AND DISADVANTAGES BASED ON SITE FEATURES																		
	Light Pack Ice < ½ m	Medium Pack Ice ½ - 2 m	Heavy Pack Ice > 2 m	Icebergs & Islands	Ice Scour	Wave Action	Tide Movement	Wave Erosion	Water Depth Limited	Soil Foundation	Water Currents	Material Availability	Transport to Site	Erection	Construction	Platform Movement	Single Season	Limited Season	Limited Access
OFFSHORE STRUCTURES																			
(A) Bottom Founded Structures																			
Unconfined Earth Atolls	H	C	C	C		C		C	A		C	C			C				H
Confined Earth Atolls	H	C	C	C				G	A		G	C			C				H
Gravity Structures	G	B	B	B					F	C	G		B	C	H				G
Jacket Structures	G	B	B	B					F	G	G		B	C	H				G
Jack-Ups	G	B	A	A					B	C	G		G	G	H				G
(B) Floating Loading Terminals																			
Mooring Barges	J	I	I	I		B	H				G		H			C		B	G
Semi-Submersibles	J	I	I	I		G	H				G		G			C		B	G
(C) Subsea Loading Connections					B					C	G				B				A
COASTAL STRUCTURES																			
(A) Bottom Founded Structures																			
Unconfined Earth	H	C	C	C		C		C	E		C	C			C				
Confined Earth	H	C	C	C				G	E		G	C			C				
Grounded Ice	H	C	C	C		C		B	E		C				C		B		
Concrete - Gravity	H	C	C	C					E	C	G				G				
Steel - Structural	H	B	B	B					E	C	G				G				
(B) Floating Mooring Structures	J	J	I	I		C	H				G		B			C		B	G

Table 1.2 Comparison of Offshore and Coastal Marine Structures

LEGEND

A	Very Serious & Insolvable
B	Very Serious & Maybe Solvable in Future
C	Very Serious & Presently Solvable
E	Less Serious & Insolvable
F	Less Serious & Maybe Solvable in Future
G	Less Serious & Easily Solvable
H	Less Serious & Easily Solvable
I	Requires Moving Off Location
J	May Require Moving Off Location
BLANK	No Significant Problem

earth. Each of these cells has a diameter of 23 m. Natural freezing strengthens the cells. Systems to artificially freeze the enclosed earth could produce sufficient strength over a greater depth range. Cells could resist buckling in collisions with pressure ridges with crushing strength up to 1,000 psi (7 MPa).

A second type of confined terminal area is produced as a caisson retained causeway. It consists of a number of steel or concrete caissons or dikes confining an area filled with sand. This has been utilized on offshore islands. The caissons are joined and pre-stressed with cables, floated onto the site and ballasted onto a prepared foundation. (Dome Petroleum Limited, Esso Resources Canada and Gulf Canada Resources Inc. - Vol. 2, Appendix 2).

A third type of confined earth structure is a hydrostatically supported sand structure. This is a column of sand in a flexible membrane which is supported by hydrostatic pressure and which depends on the mass of the sand to resist ice pressures. Only test structures have been built. (Dome Petroleum Limited, Esso Resources Canada and Gulf Canada Resources Inc. - Vol. 2, Appendix 2).

1.4.1.3 Prefabricated Gravity Structures

Massive gravity wharves have been designed which rest securely on the seabed and resist sliding, shear and overturning moment by virtue of their own weight. An example of this type of wharf is the Golden Eagle Wharf at St. Romuald on the St. Lawrence River (Vol. 2 Page 296). While not in the arctic it functions in severe winter ice conditions which in some respects exceed arctic environmental loading.

Numerous gravity structures indicate what can be used for offshore marine structure platforms, many have been built for use in the North Sea (i.e. Condeep, Ekofisk, Andoc, Ninian Platform) in water depths to over 200 m. Although most gravity platforms are constructed of concrete, some have been built of steel or a "hybrid" mixture of the two. Steel platforms are much lighter than concrete platforms and may use concrete or sand as ballast.

Lighthouse support structures have been designed frequently as gravity structures.

1.4.1.4 Pile Structures

A large number of the wharves in ice covered waters of Alaska are built of steel and supported by piles driven into the seabed. Cook Inlet wharves with open steel pile substructures have performed well. Although concrete pile wharves have had failures, it is likely that concrete piles, properly designed, can perform satisfactorily.

It appears, however, that pile supported structures cannot withstand the full force of arctic ice pack.

1.4.1.5 Jacket Structures

In deeper water, the construction of pile supported structures can be accomplished by the jacket method, similar to the oil platforms. The structure consists of a "jacket" which holds the production deck above maximum wave height, the deck and associated equipment, and a template which fastens to the legs of the jacket and through which piles are driven into the seabed. Present jackets used in the Gulf of Mexico, Persian Gulf and North Sea are an intricate framework of large diameter steel pipe. The jacket-type production platforms used in the ice affected Cook Inlet are different, having only the main legs in the path of the ice. Jacket type mooring structures are unsuitable for seas exposed to the arctic pack.

1.4.1.6 Jack-Ups

Jack-up wharves have been used during wartime and for temporary loading and unloading facilities. Conventional jack-up rigs are used for oil production in many areas where environmental conditions are not severe. They have been used in Cook Inlet in Alaska for oil and gas platforms in areas where thin ice only is present. At this time conventional jack-ups are not considered feasible for heavy ice conditions and they are unlikely to be developed for arctic waters. It is, however, quite possible that arctic platforms may use some of the concepts presently exploited by jack-ups.

1.4.1.7 Grounded Ice Islands

Experimental grounded ice islands have been built near Prudhoe Bay in an attempt to determine if such islands could survive the arctic summer. A construction dock has been built on Little Cornwallis Island of frozen fill and ice. Without artificial freezing this technique can only be used in shallow water, perhaps in depths less than 5 m.

1.4.1.8 Shoreline Structures

In order to develop work areas onshore for marine projects, shore protection is often necessary. The methods used to protect drilling islands could be applied. A method used on Melville Island could be mentioned where a protective ice berm was developed. It was covered by a gravel layer (Palmer et al. 1982 - Vol. 2, Appendix 2). Such protected ice berms could be useful in shallow waters.

1.4.2 Floating Structures

1.4.2.1 Barges

The use of barges as permanent arctic terminal structures is not yet a proven technology. Special design features will be required. One such design is a large concrete barge as proposed by Gerwick (1975 - Vol. 2, Page 92).

The main advantages of a floating structure are its dynamic response to ice forces. There is no obvious reason why large floating systems could not be designed and built of concrete, steel or a combination of both using floating barges as components.

1.4.2.2 Semi-Submersibles

Conventional semi-submersible moored structures are not feasible for use in ice covered waters due to their many legs and braces which present a vulnerable cross section to moving ice. It is possible that other types of semi-submersible vessels may be developed for use in ice covered waters. Semi-submersibles do not create ice free water for mooring, which limits their usefulness.

1.4.3 Subsea Structures

1.4.3.1 Single Point Mooring Terminals

One of the most attractive methods of producing hydro carbons in ice covered waters is that of subsea completion and production below the effects of ice and waves. Pipe lines carry product to onshore processing facilities and/or to tanker terminals. The standard type single point mooring buoy system is not considered viable in arctic conditions due to its vulnerability to ice damage. However, a retractable single point mooring buoy system is considered to be viable.

1.4.3.2 Pipelines

Oil or gas fields further offshore will pose problems due to long pipelines to shore, and to tanker ports. Ice scour is one main problem. Near shore scour of the pipeline is a definite hazard and tunnelling may be necessary in some areas to avoid scour. For pertinent papers relating to ice scour, refer to Volume 2, Chapter 1.4.

1.5 Logic for Planning and Design

For areas where ice is a major factor, the following logic diagram may be used as an aid to the analytical process (Figure 1.4).

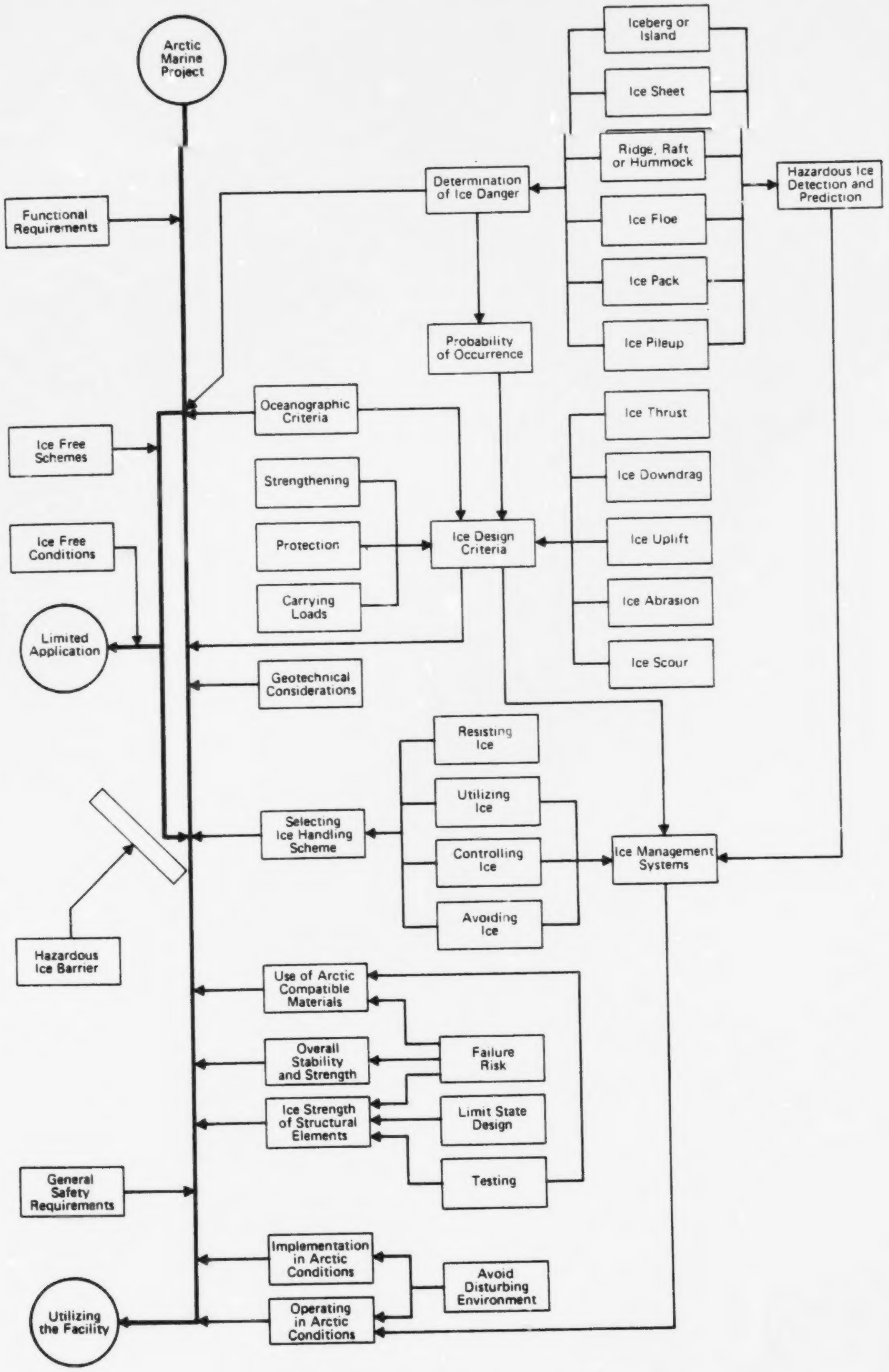

Arctic Marine Project
Iceberg or Island
Ice Sheet
Ridge, Raft or Hummock
Ice Floe
Ice Pack
Ice Pileup
Determination of Ice Danger
Hazardous Ice Detection and Prediction
Functional Requirements
Probability of Occurrence
Oceanographic Criteria
Ice Free Schemes
Strengthening
Protection
Carrying Loads
Ice Design Criteria
Ice Thrust
Ice Downdrag
Ice Uplift
Ice Abrasion
Ice Scour
Ice Free Conditions
Limited Application
Geotechnical Considerations
Resisting Ice
Utilizing Ice
Controlling Ice
Avoiding Ice
Selecting Ice Handling Scheme
Ice Management Systems
Hazardous Ice Barrier
Use of Arctic Compatible Materials
Overall Stability and Strength
Failure Risk
Ice Strength of Structural Elements
Limit State Design
Testing
General Safety Requirements
Implementation in Arctic Conditions
Avoid Disturbing Environment
Operating in Arctic Conditions
Utilizing the Facility

Figure 1.4 Logic for planning and design.

CHAPTER 2

MARINE ENVIRONMENT

2. MARINE ENVIRONMENT

2.1 Bathymetry

Detailed information on the bathymetry of the Canadian Arctic is available from hydrographic charts published by Canadian Hydrographic Surveys, Ottawa; "Physical Oceanography in Arctic Canada" (Collin and Dunbar 1964 - Vol. 2, Appendix 2) and "Arctic Data Compilation and Appraisal" (Conford, A.B. et al.) published by Institute of Ocean Sciences, Sidney, B.C. (Vol. 2, Appendix 1).

As general information to the user of this Handbook, the bathymetry of five Canadian Arctic Regions (Grand Banks excluded) is briefly presented as follows (Figure 1.1):

2.1.1 Arctic Archipelago

The Canadian Archipelago represents the drowned northern extension of Continental North American coastline (Collin and Dunbar 1964). Water depths in the Archipelago range from 100 m to 500 m with the deepest waters being found at the eastern and western extremeties. The typical depth of the continental shelf bordering the western Arctic Islands is about 550 m with a width from only a few kilometres along the north coast of Ellesmere Island, to over 150 km in the area of the Beaufort Sea. The continental shelf on the eastern coast is at a depth of about 200 m and seldom more than 50 km wide. The usual steep declivity of the sea floor in nearshore areas, coupled with absence of large rivers, greatly limit the presence of extensive offshore and tidal flats.

2.1.2 Beaufort Sea

The bathymetry of the area is characterized by several distinctive features. A broad, shallow continental shelf borders the mainland coast and the west coast of Banks Island. The edge of the shelf lies between the 100 and 200 m isobaths and may be as far as 100 km from shore, with depths of less than 10 m being found as much as 30 km offshore. Depths increase rapidly over the continental slope, being particularly large from the 100 m and 1,000 m isobath; beyond, the bottom depth increases more gradually with distance offshore over the continental rise, and eventually the bottom levels out at about 3,500 m, in the relatively flat Canada Abyssal Plain.

The shelf is broken in two places in the Beaufort area: in the west off Herschel Island, where the Herschel Canyon has depths of 100 m or more within 35 km of the coastline; and in the east, where a deep trough (325 m) connects Amundsen Gulf with the Beaufort Sea. Amundsen Gulf proper has depths in excess of 600 m, and relatively steep sides.

A similar trough connects the Beaufort Sea with M'Clure Strait in the northeastern portion of the area (Cornford et al.).

2.1.3 Hudson Bay

Hudson Bay is large and relatively shallow inland sea with an area of approximately 520,000 km^2.

The west-central portion of Hudson Bay is a broad relatively deep area with water depths greater than 120 m.

Hudson Bay is bordered by low-lying shores with extensive tidal flats (15 to 25 km in width) along the western and south-western coast. Mid-channel depths in Hudson strait range from 550 m in the eastern end to 350 m in the western extremes.

2.1.4 Baffin Bay

Baffin Bay forms a deep, enclosed depression between the Canadian Arctic Archipelago and west Greenland. The maximum depth in the Bay is approximately 2,300 m.

The Davis Strait ridge between Baffin Island and Greenland at 66°N clearly form a definite sill with a limiting depth of less than 730 m between the deeper waters of Baffin Bay and the Labrador Sea.

2.1.5 Labrador Shelf

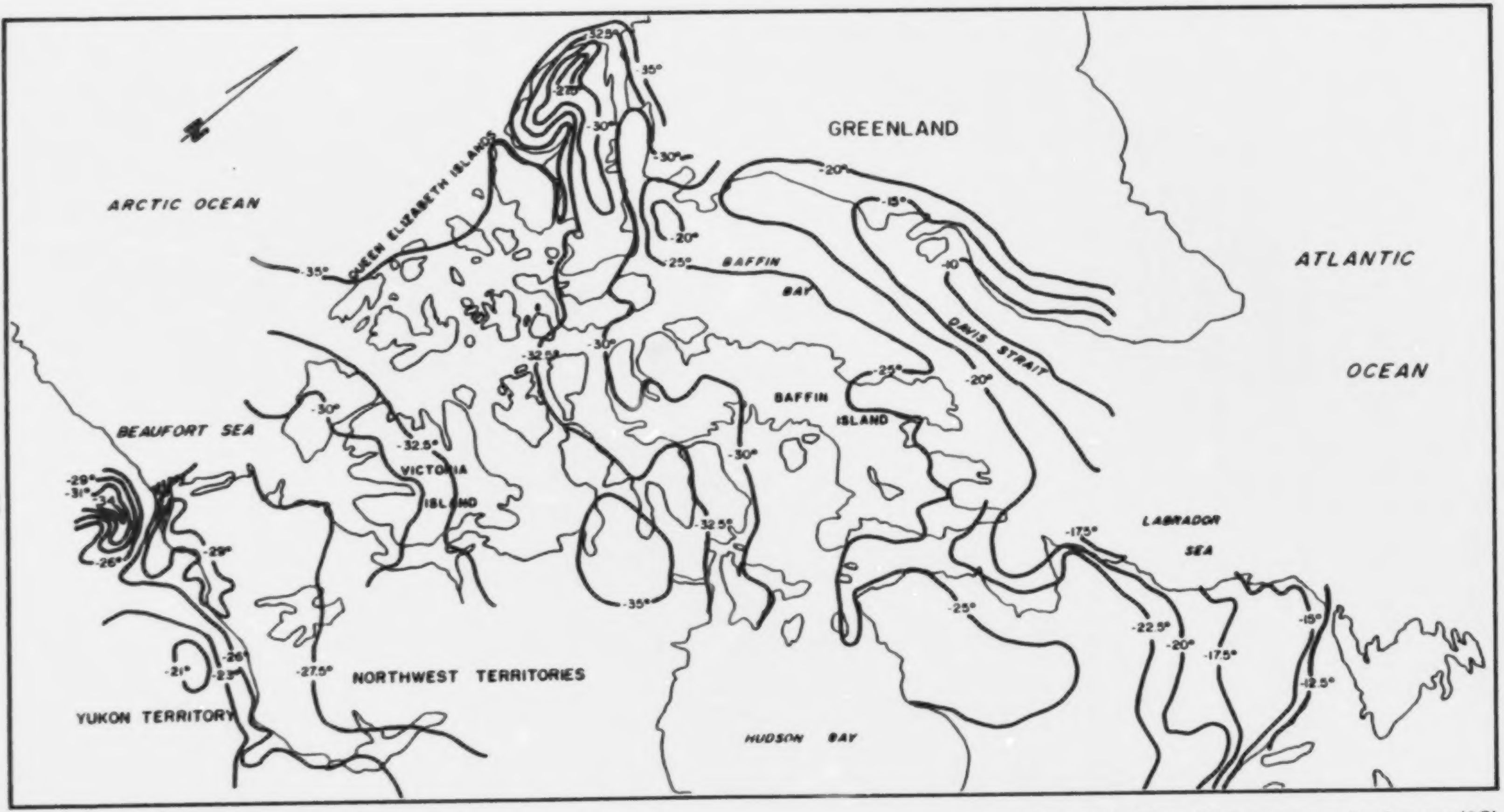
The coast of Labrador is indented by many irregular bays and inlets. It extends northerly from the Strait of Belle Isle, to Cape Chidley on the southeastern side of the entrance to Hudson Strait. A narrow continental shelf extends parallel to the Labrador Coast with average width of about 200 km with a very steep continental slope.

2.2 Meteorology

2.2.1 Atmospheric Factors

2.2.1.1 Air Temperature

The Arctic regions are characterized by extremely low winter air temperatures (Figure 2.1). Mean daily temperatures in the Arctic Islands average -33.8°C, -35.3°C and -33.5°C for the months of January, February and March, respectively (Table 2.1) and remain below freezing for 10 months of the year while mean January temperatures for the Beaufort Sea average -32°C and remain below freezing for eight months of the year. Although air temperatures are lower in the Baffin Bay - Davis Strait regions of the Arctic as a result of the warm, north moving current along the Greenland Coast, mean daily temperatures for January and February still average between -20°C and -25°C. Average daily January temperatures in Hudson Bay range from -32°C along the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DAVIS STRAIT
BAFFIN
ISLAND
BEAUFORT SEA
VICTORIA
ISLAND
LABRADOR
SEA
NORTHWEST TERRITORIES
YUKON TERRITORY
HUDSON BAY
-32.5°
-35°
-27.5°
-30°
-30°
-20°
-15°
-10°
-20°
-25°
-35°
-30°
-32.5°
-30°
-25°
-20°
-30°
-32.5°
-29°
-31°
-34
-26°
-29°
-26°
-23°
-21°
-27.5°
-35°
-32.5°
-17.5°
-25°
-22.5°
-20°
-17.5°
-15°
-12.5°

Figure 2.1 Mean Air Temperature for January (°C)
Source: AES

	Years of Data	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Point Barrow	40	-20.8	-28.1	-20.8	-18.1	- 7.5	1.1	4.2	3.3	- 0.8	- 8.3	-17.8	-23.9
Barter Island	12	-26.9	-29.7	-20.6	-18.1	- 6.1	1.1	4.7	4.2	- 0.3	- 8.6	-17.8	-25.6
Tuktoyaktuk	15	-27.2	-29.2	-24.9	-16.9	- 4.6	4.7	10.3	8.7	2.3	- 6.9	-19.3	-25.2
Cape Parry	•	-28.5	-30.4	-26.1	-17.4	- 6.1	1.7	5.7	5.3	0.8	- 6.5	-18.2	-24.5
Sachs Harbour	•	-29.7	-30.9	-27.3	-19.2	- 7.3	2.2	5.6	4.3	- 1.8	-11.6	-21.7	-26.7
Clinton Point	•	-27.4	-28.9	-24.4	-16.2	- 5.1	3.3	7.4	6.5	0.8	- 7.1	-17.6	-23.1
Holman	25	-29.6	-30.8	-26.6	-17.7	- 6.4	3.7	7.6	6.4	0.1	- 9.1	-19.7	-24.8
Coppermine	30	-29.4	-30.9	-26.1	-17.7	- 5.7	3.5	9.3	8.6	2.3	- 6.3	-19.5	-25.7
Byron Bay	•	-32.8	-33.4	-28.9	-20.9	- 8.9	2.4	9.1	7.3	- 0.3	-10.3	-22.9	-28.6
Cambridge Bay	25	-33.7	-34.6	-30.1	-22.2	- 9.6	1.5	8.2	6.9	- 0.5	-11.1	-23.8	-29.6
Gladman Point	•	-34.4	-35.5	-30.8	-22.3	- 9.7	0.6	7.7	6.0	- 1.0	-10.9	-23.7	-29.9
Spence Bay	15	-34.4	-34.6	-31.5	-21.9	-10.0	0.8	7.1	6.5	- 0.9	-11.9	-23.7	-30.2
Pelly Bay	•	-33.1	-33.2	-28.9	-20.0	- 9.7	-0.6	6.9	5.2	- 2.9	-12.2	-22.6	-28.1
Mackar Inlet	•	-32.6	-32.2	-27.4	-19.5	- 9.4	-0.7	6.3	4.9	- 3.4	-12.1	-21.5	-27.1
Hall Beach	•	-31.7	-31.6	-28.3	-20.0	- 8.8	0.3	5.4	4.9	- 0.6	-10.2	-20.9	-26.9
Longstaff Bluff	•	-28.4	-28.2	-26.1	-18.0	- 7.2	1.0	6.9	6.4	- 0.8	- 9.2	-18.1	-24.8
Coral Harbour	25	-30.4	-29.5	-24.5	-16.4	- 6.5	2.0	8.6	7.5	1.0	- 7.7	-17.1	-24.5
Mould Bay	20	-33.8	-35.6	-32.4	-23.6	-10.9	-0.3	3.7	1.7	- 6.6	-17.8	26.6	-31.3
Rea Point	•	-33.0	-35.1	-33.2	-24.1	-10.9	-0.1	4.7	1.7	- 5.4	-16.3	-26.7	-30.1
Isachsen	20	-35.1	-36.4	-34.4	-25.6	-11.7	-0.8	3.3	1.1	- 8.8	-19.4	-28.2	-32.5
Eureka	20	-36.6	-37.7	-36.7	-27.6	-10.1	2.3	5.5	3.6	- 7.7	-21.8	-30.7	-34.8
Alert	20	-32.1	-33.3	-33.0	-24.7	-11.2	-0.6	3.9	0.9	-10.1	-19.7	-26.1	-29.8
Resolute	20	-32.6	-33.5	-31.3	-23.1	-10.7	-0.3	4.3	2.7	- 4.9	-14.7	-24.2	-28.8
Arctic Bay	20	-29.8	-31.1	-27.7	-19.8	- 7.6	2.1	5.8	4.8	- 1.6	-11.1	-21.1	-26.8
Pond Inlet	•	-30.9	-32.3	-30.8	-21.6	- 8.8	1.3	5.1	4.7	- 1.1	-10.3	-21.2	-28.2
Clyde	25	-26.9	-27.4	-26.3	-18.7	- 6.9	0.9	4.6	4.0	- 0.1	- 6.6	-16.9	-24.2
Cape Hooper	•	-25.1	-25.7	-24.1	-16.8	- 7.3	-0.4	4.8	2.9	- 1.8	- 7.5	-15.7	-22.0
Broughton Island	•	-24.2	-24.9	-23.4	-16.6	- 7.2	-0.6	5.0	3.6	- 1.9	- 7.7	-15.2	-21.3
Cape Dyer	•	-22.2	-23.0	-22.4	-14.7	- 5.4	0.6	5.6	4.6	- 1.1	- 7.3	-14.8	-20.4
Brevoort Island	•	-22.3	-21.1	-18.9	-14.2	- 5.1	0.4	4.2	4.1	- 0.2	- 5.2	-10.8	-16.9

Source: Atmospheric Environment Center

• Averages are based on 5 - 10 years record and have been adjusted after comparison with longer term stations.

Table 2.1 Mean Daily Temperatures

northwestern coast to -23°C in the southeast. Average monthly January temperatures along the Labrador coast vary from -19.8°C at Resolution Island in the north to -9.0°C at Battle Harbour in the south.

Low temperatures in the Arctic hamper the execution of most activities. Below temperatures of -18°C, outdoor operations and maintenance become difficult. For instance, ordinary carbon steels become brittle near this temperature and their strength decreases as the temperature further decreases. Welding techniques have to account for extremely rapid cooling with consequent changes in the metallurgical properties of the materials used and the rapid freezing of materials containing water is a constant concern. Other problems involve plastics and rubber becoming brittle, loss of battery capacity, and the gelling of fuel and lubricants. The situation becomes more serious at -30°C and activities are very limited at -40°C.

Mean daily temperatures in July in the Arctic Islands generally average a few degrees above 0°C, however, they may occasionally approach temperatures of 15°C to 20°C (Figure 2.2).

In an environment of extremely low air temperature the combined effect of it and a moderate wind create a wind chill factor that dramatically lowers the effective temperature and makes outdoor activity extremely dangerous.

Various authors have contributed to arrive at a formula which measure the cooling effect on a surface due to the combination of temperature and wind.

$$T_W = 33 - [(0.288 \sqrt{V} + 0.45 - 0.019\ V)\ (33 - T)]$$

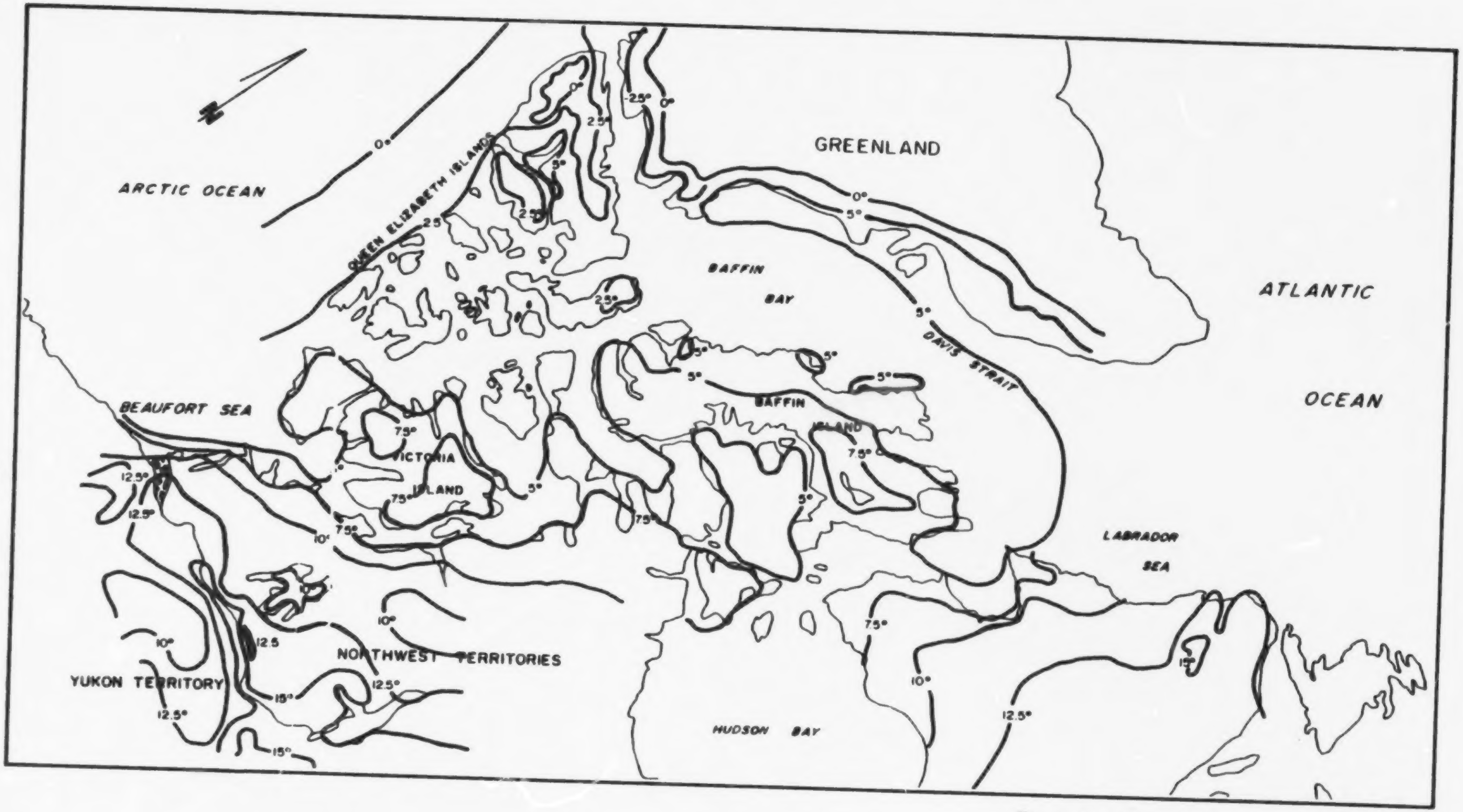
where:

T_W = wind-chill temperature (°C)
V = wind speed in km/hr.
T = air temperature and an assumed neutral skin temperature of 33°C (Burns 1973)

For example, with winds at 32 km per hr., a temperature of -32°C becomes effectively -64°C and creates a condition whereby exposed facial areas can freeze in less than a minute on the average person (Figure 2.3).

Thermal Ice Forces

Variations in air temperature cause variations in the temperature of ice and produce thermal ice forces. A recent thorough review of various methods to estimate temperature ice forces has been carried out by Kjeldgaard and Carstens (Carstens 1980 - Vol. 2, Appendix 2).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LABRADOR SEA
HUDSON BAY
NORTHWEST TERRITORIES
YUKON TERRITORY
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0°
-2.5°
2.5°
5°
7.5°
10°
12.5°
15°

Figure 2.2 Mean Air Temperature for July (°C)
Source: AES

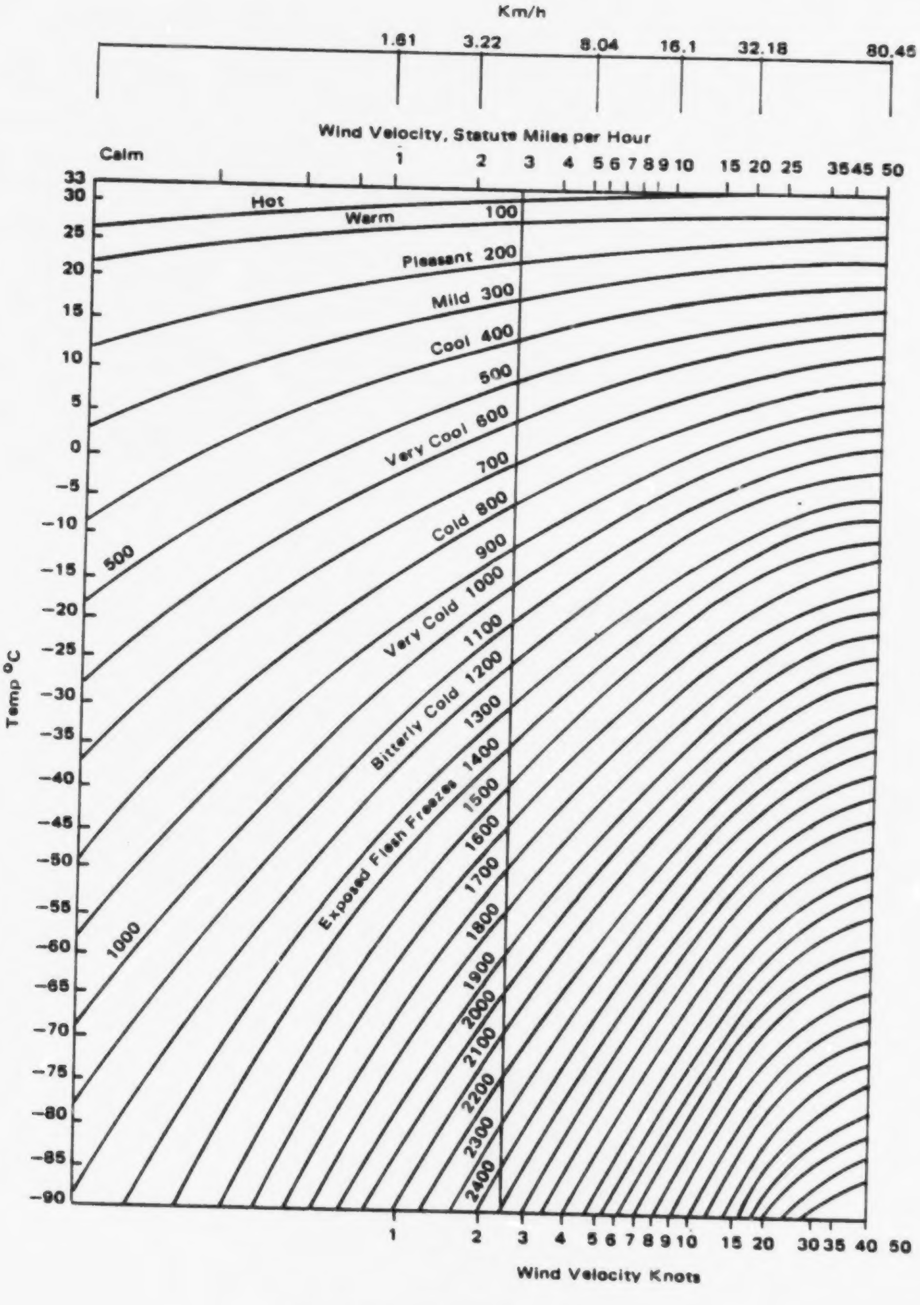


Figure 2.3 Wind-Chill Nomogram

To obtain equivalent wind-chill temperature, select current temperature valve (°C) at left side of curve; move horizontally to the right to a point vertically below the current wind velocity (k/mph); follow to the left and downward to the nearest parallel line until you intersect the 5, k/mph vertical line; go back horizontally to the left and read off the equivalent wind-chill temperature.

The usual practice in North America for fresh water bodies has been reviewed by the Inland Waters Branch, Department of the Environment (Inland Waters Branch 1971 - Vol. 2, Appendix 1). According to this review the thrust may be assumed to vary linearly with the ice thickness at a rate of 240 kPa (5000 lb./sq. ft.). This gives a load of 240 kN per 1 metre thickness of fresh water ice.

Essentially, the main parameters in ice stresses from thermal variations appears to be: (i) rise of air temperature, (ii) viscosity of ice, (iii) elasticity of ice, (iv) ice thickness, and (v) restraints on ice movement.

Values obtained by various formulae are discussed in the chapter on ice technology.

2.2.1.2 Precipitation

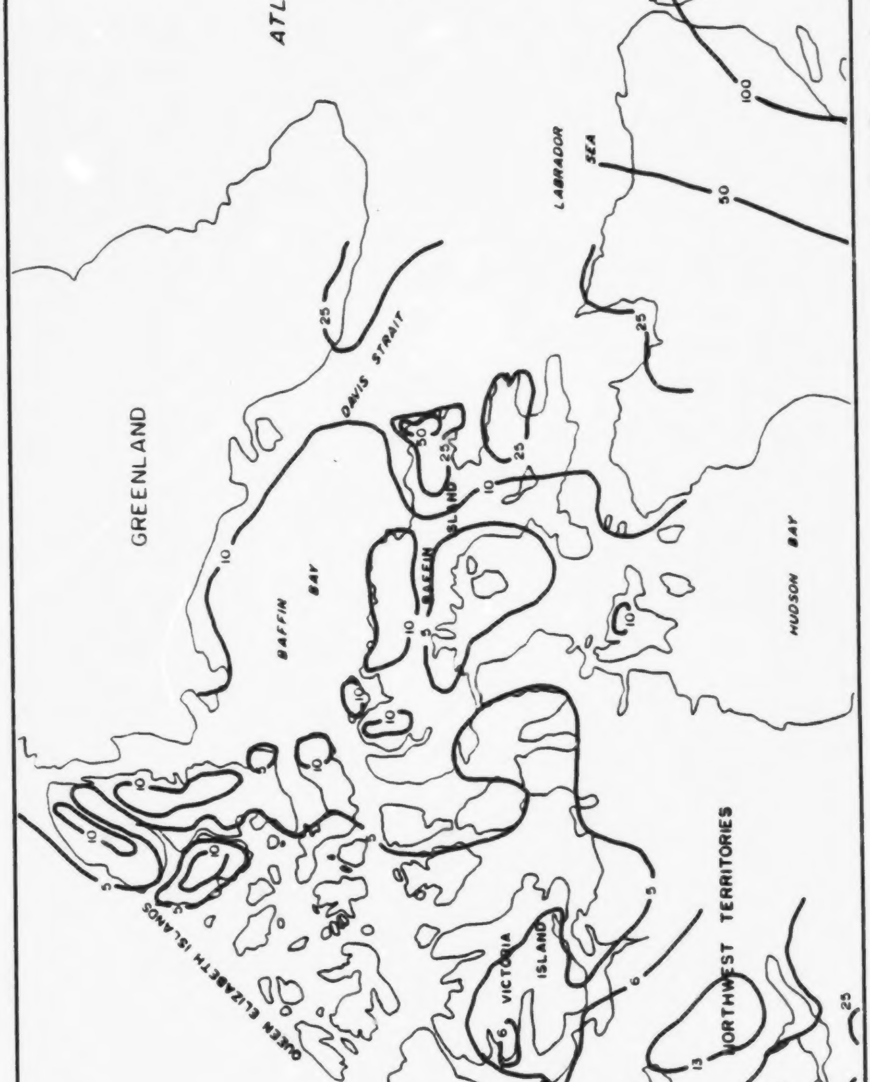
Across the Arctic regions, as a whole, annual precipitation is generally very light and decreases steadily as one proceeds northwards (Figures 2.4 and 2.5).

September and October are the stormiest months of the year over most of the Arctic. With the shortening autumn days and the annual southward displacement of the paths followed by the storm centres, progressively colder outbreaks of air from the Polar seas affect the Canadian Arctic. During these months the waters of the bays and channels are largely unfrozen and the relative warmth and moisture they provide lead to instability and frequent snowfalls. The greater portion of the 50 to 125 cm annual snowfall occurs during these months. The lands of the eastern Arctic are mostly snow-covered by September 15, while the winter snow cover is not usually established over the Mackenzie Delta area until the end of the month (Figure 2.6).

As winter deepens and the land and sea surfaces become uniformly snow and ice covered the Arctic is relatively free of clouds and snowfall is light. Even so, light snow may be reported 15 to 20 percent of the time (Table 2.2). Although snowfall may be fairly uniform over a region, it is quickly redistributed by the wind. Freshly fallen snow rapidly increases in density and the snow cover soon becomes compact and capable of supporting a man. In general, the winter snow cover averages about 30 to 40 cm although along the southeast coast of Baffin Island depths in excess of 250 cm have been recorded.

May marks an abrupt change in the cloud pattern, although precipitation is still in the form of snow. The late spring is associated with an increase in snow intensity as moist northern air masses begin once again to invade the northern regions.

With the exception of southeastern Baffin Island, where small amounts of rain or freezing rain may occur in almost any month of the year, rainfall over the Canadian Arctic is generally confined to the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BAFFIN BAY
DAVIS STRAIT
LABRADOR SEA
HUDSON BAY
BAFFIN ISLAND
VICTORIA ISLAND
QUEEN ELIZABETH ISLANDS
NORTHWEST TERRITORIES
YUKON TERRITORY
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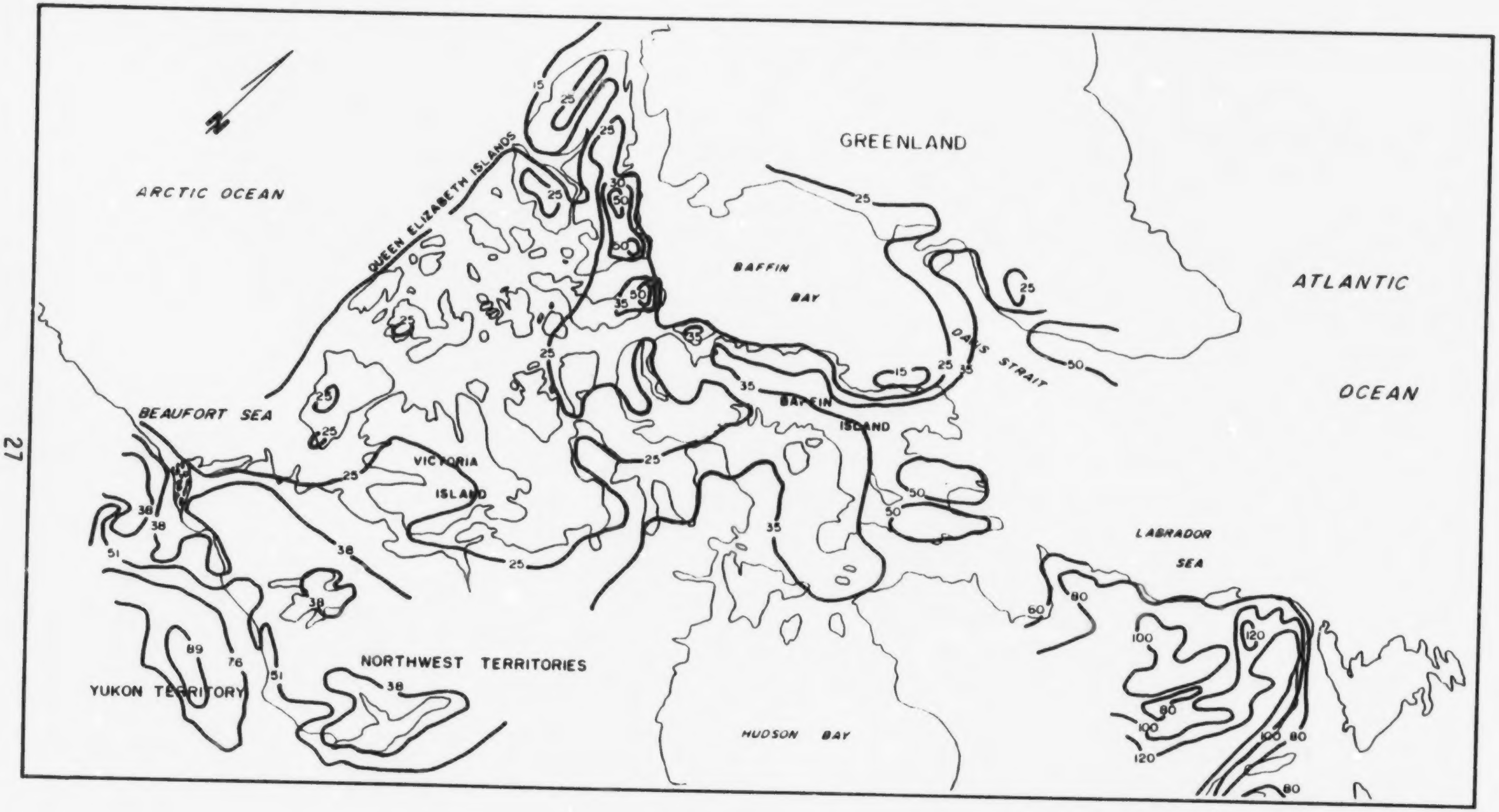
Figure 2.4 Mean Total Precipitation for January (mm)
Source: AES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BEAUFORT SEA
VICTORIA ISLAND
BAFFIN ISLAND
LABRADOR SEA
NORTHWEST TERRITORIES
YUKON TERRITORY
HUDSON BAY
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30
35
50
60
80
100
120
38
51
76
89

Figure 2.5 Mean Total Precipitation for July (mm)
Source: AES

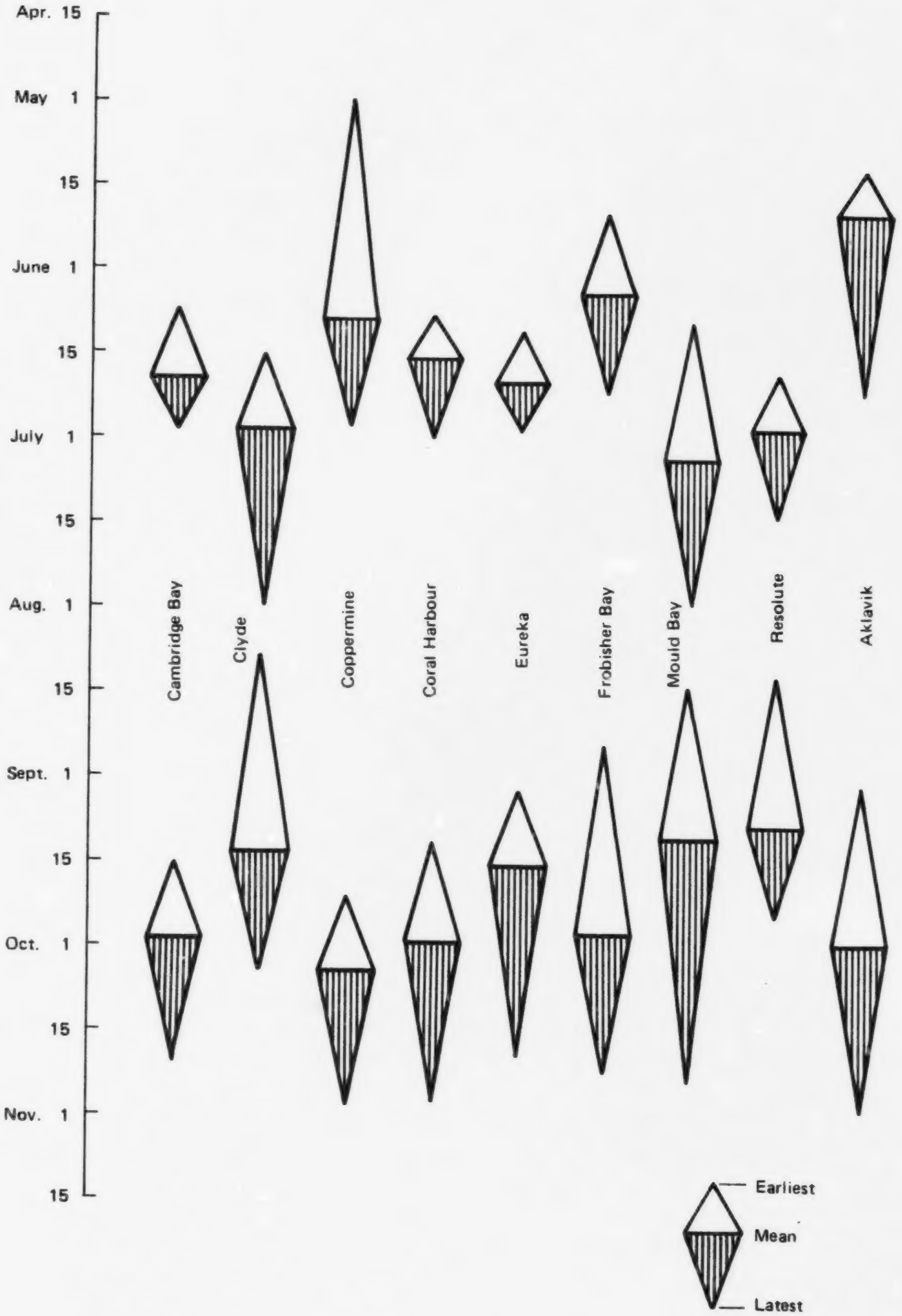


Figure 2.6 Dates of First and Last Snow Cover
(From Thomson, H.A., Climate of Hudson Bay – Volume 2, Appendix 2)

	Rain	Snow	Freezing Precipitation
January			
Frobisher Bay	1	21	*
Resolute	0	11	0
Mould Bay	0	12	0
Sachs Harbour	0	10	0
Cape Parry	0	15	*
April			
Frobisher Bay	*	18	*
Resolute	0	16	0
Mould Bay	0	10	*
Sachs Harbour	0	11	0
Cape Parry	0	21	1
July			
Frobisher Bay	19	0	0
Resolute	12	5	*
Mould Bay	11	5	*
Sachs Harbour	7	2	*
Cape Parry	12	2	1
October			
Frobisher Bay	2	34	1
Resolute	0	32	1
Mould Bay	0	20	*
Sachs Harbour	*	22	*
Cape Parry	*	46	*

*Less than 0.5 per cent.

Table 2.2 Percentage Frequency Occurrence of Precipitation Types (From hourly or three-hourly observations 1957 – 1966 - from Thompson, H.A., Climate of Hudson Bay – Volume 2, Appendix 2)

months June to early September. July and August are usually the wettest months, with monthly rainfall totals of about 5 cm in southern sections, decreasing northward to less than one inch over the Arctic Islands. While precipitation is mainly related to frontal and cyclonic activity throughout the Arctic, the effects of topography are particularly noticeable in the east, where windward slopes, exposed to the moist air from the north Atlantic, have considerably more cloudiness and precipitation than lee areas. Days with precipitation are more frequent than one would expect from the low monthly rainfall totals. During July and August periods of light rain or drizzle occur on the average on one day in three. Rainfall is extremely variable from year to year and despite the fact that average amounts are low, heavy rains have been reported on occasion in the Arctic. These are associated with northward moving cyclones that bring with them supplies of moisture from more southerly latitudes. For example, during an exceptional storm on July 21, 1973, more than 25 mm of rain fell on Rae Point with the effects of the storm being felt over the entire Arctic Islands.

Over the Arctic Islands, rainfall occurring during the short summer season, amounts to about the same as the total water equivalent of snowfall during the nine months of winter. Together they total less than 13 cm. Annual precipitation increases southward to 20 to 25 cm over the mainland and to more than 60 cm along the southeast coast of Baffin Island.

The Hudson Bay region receives most of its precipitation during the months of July and August in the form of rainfall. Maximum monthly snowfall occurs in the northwestern part of Hudson Bay during the months of October and November and in the southeastern sector during the months of November, December and January. Total precipitation averages 680 mm per year in the southeastern part; approximately 2.5 times the total yearly precipitation in the northern part of Hudson Bay is a result of the moderating effects of the open water zones of Hudson Bay.

Mean annual precipitation decreases from about 950 mm over southern coastal Labrador to nearly 310 mm at Resolution Island (Bursey et al. 1977 - Vol. 2, Appendix 2). Snow accounts for about 43% of annual precipitation over southern coastal Labrador and 50% at Resolution Island. Maximum monthly snowfall along the Labrador coast (October through March) is roughly 3 times the monthly mean, while maximum monthly rainfall (May through October) is approximately 2.3 times the monthly mean. The rainiest 3 month period for both southwest Greenland and southern coastal Labrador is usually July through September when 40 to 50% of annual rain accumulates. However, moving northward along coastal Labrador the percentage steadily increases until a value of approximately 73% is attained at Resolution Island.

2.2.1.3 Barometric Pressure

The major circulation features in the lower levels of the Arctic atmosphere may be illustrated by referring to the mean sea level pressure charts which depict the favoured positions of high and low pressure systems (see Figures 2.7 and 2.8).

Broadly speaking, these charts indicate that although low pressure areas periodically penetrate the Canadian Arctic during the period of November to May, the usual circulation in winter is anticyclonic. The January map shows that the sea level circulation is dominated by 2 large cells, 1 continental high and 1 oceanic low located over the Mackenzie Basin and Baffin Bay respectively. The combination of these pressure systems maintain a general NW to SE circulation. Low pressure areas generally cross Canada at latitudes south of Hudson Bay during this period and only affect the Arctic as they recur northward into the region of high cyclonic activity over Baffin Bay.

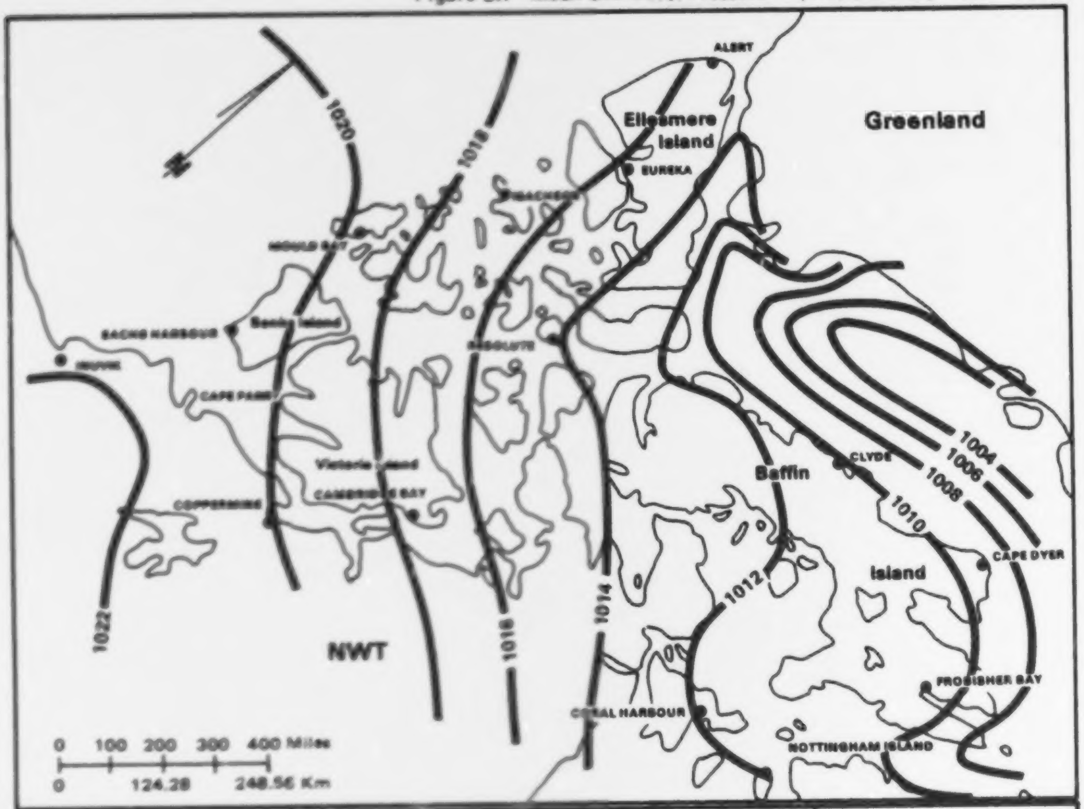
The January pattern generally persists into March. Thereafter the mean pressure field undergoes rapid change with a pronounced weakening of the low cell and of the Siberian continental high, and a relative intensification of high pressure over the Polar Ocean, caused partly by the North American high which shifts closer to the Pole. It is in the spring that strong anticyclonic activity is most likely to occur over the central Arctic. In the warm season, the central Polar Ocean is under a feeble low pressure area, while weak anticyclones are found over the peripheral areas of the Arctic Ocean, covering the Pacific section, with a ridge over the Beaufort Sea.

By October the pressure patterns show a superficial resemblance to the spring conditions. Relatively high pressure occurs over the central Polar Ocean, and the sub-polar lows are back in their customary positions. The mean pattern, however, represents a compromise between contrasts of vigorous cyclonic circulation systems and calm periods of anticyclonic control. The Icelandic low which affects Baffin Bay approaches characteristic wintertime strength. The high over Alaska-Yukon is not yet established, but the pressure begins building over the Canadian Archipelago, to the northeast of its wintertime position.

2.2.1.4 Winds, including Effect on Ice

The distributions of surface wind directions and speeds are shown in the wind roses for selected locations across the Arctic (Figures 2.9 and 2.10). Extreme wind speeds and average number of hours of strong winds for a number of stations are shown in Tables 2.3 and 2.4. Examination of these statistics brings out the effect on winds of local topography at several coastal locations. While wind speeds over the seas can be explained by the pressure gradients associated with low and high pressure areas and the stability of the air over the sea surface, local effects are especially important as causes of strong winds. There are two significant local influences:

Figure 2.7 Mean Sea Level Pressure – (mb) (January 1931 - 1960)


N
ALERT
Ellesmere Island
EUREKA
ISACHSEN
Greenland
MOULD BAY
SACHS HARBOUR
Banks Island
INUVIK
CAPE PARRY
RESOLUTE
Victoria Island
CAMBRIDGE BAY
COPPERMINE
Baffin
Island
CLYDE
CAPE DYER
FROBISHER BAY
CORAL HARBOUR
NOTTINGHAM ISLAND
NWT
1022
1020
1018
1016
1014
1012
1010
1008
1006
1004
0 100 200 300 400 Miles
0 124.28 248.56 Km

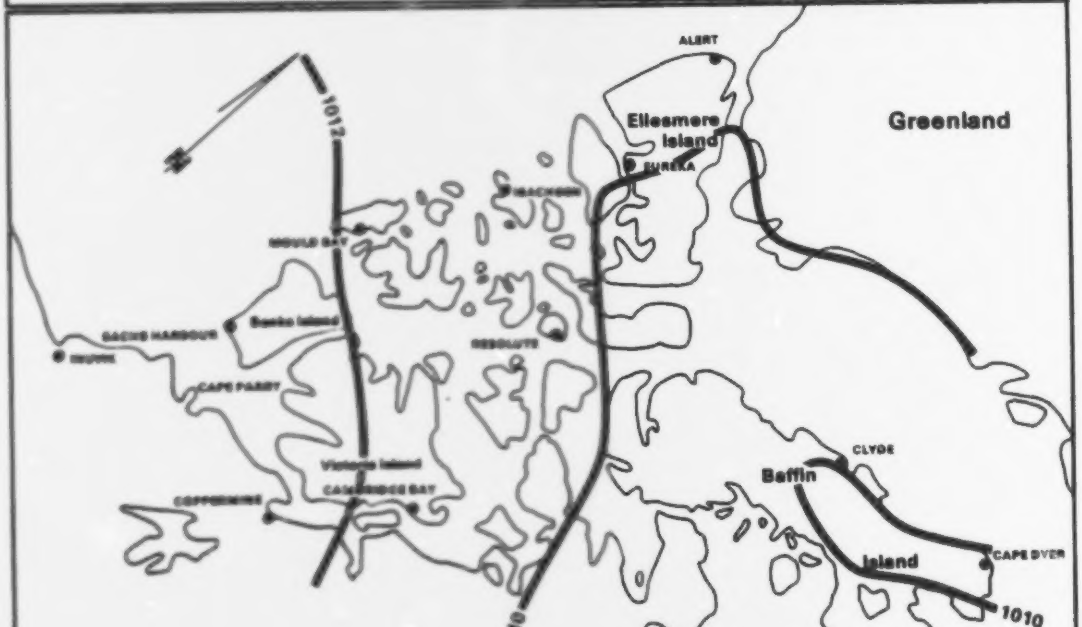
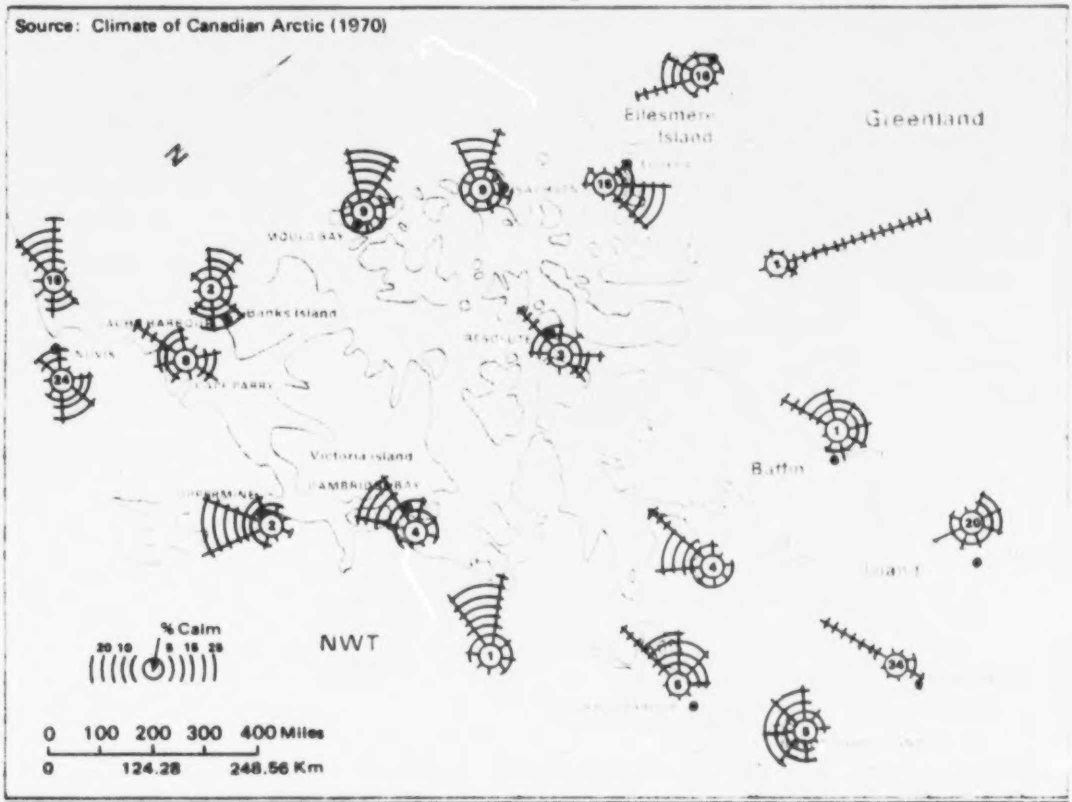

N
ALERT
Ellesmere Island
EUREKA
ISACHSEN
Greenland
MOULD BAY
SACHS HARBOUR
Banks Island
INUVIK
CAPE PARRY
RESOLUTE
Victoria Island
CAMBRIDGE BAY
COPPERMINE
Baffin
Island
CLYDE
CAPE DYER
FROBISHER BAY
CORAL HARBOUR
NOTTINGHAM ISLAND
NWT
1012
1010
1010
1008
0 100 200 300 400 Miles
0 124.28 248.56 Km

Figure 2.8 Mean Sea Level Pressure – (mb) (July 1931 - 1960)

Source: AES

Figure 2.9 Direction Frequencies of January Winds


Source: Climate of Canadian Arctic (1970)
N
Ellesmere Island
Greenland
MOULD BAY
SACHS HARBOUR
Banks Island
INUVIK
CAPE PARRY
RESOLUTE
Victoria Island
CAMBRIDGE BAY
COPPERMINE
Baffin
Island
NWT
% Calm
20 10 5 15 25
0 100 200 300 400 Miles
0 124.28 248.56 Km

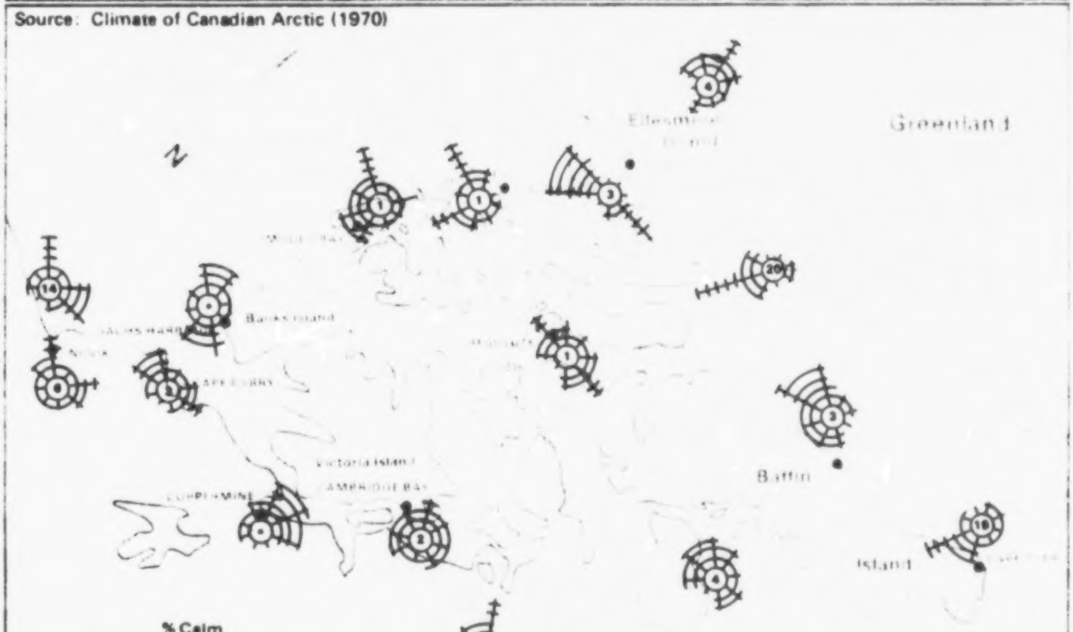

Source: Climate of Canadian Arctic (1970)
N
Ellesmere Island
Greenland
MOULD BAY
SACHS HARBOUR
Banks Island
INUVIK
CAPE PARRY
RESOLUTE
Victoria Island
CAMBRIDGE BAY
COPPERMINE
Baffin
Island
NWT
FROBISHER BAY
% Calm
20 10 5 15 25
0 100 200 300 400 Miles
0 124.28 248.56 Km

Figure 2.10 Direction Frequencies of July Winds
Source: AES

1. Onshore winds along the coastlines are deflected in directions nearly parallel to the shore and increase in speed. Similarly, the prevailing directions in straits and fjords are usually along the channel and the speed increases as the channel narrows.

2. Along precipitous coastlines where there is a snow-covered area in the interior to collect a pool of relatively cold air, strong winds may occur when this dense, cold air drains seaward. Such winds are often of short duration but may extend several miles to sea.

Sheltered locations, such as Inuvik, experience light winds which are not representative of winds offshore. Conversely, maximum reported wind gusts such as at Stokes Point, Resolute and others reflect the influence of local topography.

Station	Maximum Speed km/hr.	Direction
Alert	154	South
Cambridge Bay	89	Northwest
Cape Dyer	130	Northwest
Cape Parry	104	Northwest
Clyde	80	North
Frobisher Bay	130	Northwest
Hall Beach	100	Northwest
Mould Bay	104	East
Resolute	141	East
Sachs Harbour	89	Northeast

Source: Climate of Canadian Arctic (AES)

Table 2.3 Maximum Observed Hourly Wind Speed and Direction

Excluding local effects, winds average 18 to 22 km/hr. at most stations from December through April, are only slightly lower during the summer months and reach average speeds of more than 28 km/hr. in the autumn.

The average values are somewhat misleading in the winter months since most stations report calm conditions up to 30% of the time. At exposed stations in the eastern Arctic in winter 30% of the winds are stronger than 31 km/hr., 10% exceed 52 km/hr. and less than 5% are greater than 63 km/hr. Low pressure areas moving up Davis Strait in winter give the coastlines of the eastern Arctic their strongest winds. These winds generally maintain their highest speeds over periods exceeding 24 hours and two- and three-day blows are not unusual during any month from October through April. Further removed from the cyclonic activity in Davis Strait, wind velocities in the western Arctic are somewhat lower.

	Years of Data	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Most Common Direction
Inuvik 25 kts	10	2	*	1	1	*	*	*	1	1	*	1	3	NW
Cape Parry 25 kts	10	40	22	41	67	29	36	16	26	31	66	49	59	Variable
Cambridge Bay 25 kts	10	73	47	31	26	30	28	30	28	44	72	36	49	NW
Sachs Harbour 30 kts	10	9	5	3	8	5	5	3	5	10	13	6	11	SE
Mould Bay 25 kts	10	98	53	41	35	30	44	35	40	60	52	41	71	NW & NE
Isachsen 25 kts	10	156	121	79	56	74	63	42	47	64	61	58	113	N
Eureka 25 kts	10	36	13	4	8	12	16	13	7	9	12	7	19	S
Alert 25 kts	10	54	60	35	46	51	50	96	44	58	64	50	56	SW
Resolute 25 kts	10	147	133	118	112	97	113	80	131	82	125	105	140	SE
Hall Beach 25 kts	10	62	81	55	42	57	30	15	34	116	126	110	53	NW
Cape Dyer 25 kts	10	100	61	50	41	42	26	10	12	47	64	65	93	NW
Coral Harbour 25 kts	10	121	60	34	57	70	48	34	59	60	79	92	102	NE
Frobisher 25 kts	10	115	103	81	91	101	49	28	38	74	106	89	99	E & NW

Source: Fenco Arctic Atlas

Table 2.4 Average Number of Hours of Strong Winds
(Note: 25 knots - 46.32 km/sec.)

Although average wind velocities at most coastal stations in summer are not too different from winter values, there are few calm conditions in summer and consequently there is a lower percentage of winds in the speed ranges above 37 km/hr. Usually winds reach gale force on only one or two days each month in summer (Table 2.5). Surface winds are also more variable in direction than in winter since their patterns are complicated by the low pressure areas which affect the region. The complete daily reversal of direction in the ordinary land and sea breeze effect, so common along the coasts in southern latitudes, does not normally occur in the Arctic, although when the pressure gradient is weak and skies are clear in late summer an onshore component may develop during the afternoon.

Station	Jan.	Mar.	May	July	Sept.	Nov.	Annual
Alert	3	2	2	2	1	2	25
Cambridge Bay	1	*	*	*	*	*	3
Cape Dyer	4	2	1	*	1	2	30
Cape Parry	1	*	0	0	*	*	3
Clyde	1	0	*	0	*	*	2
Frobisher Bay	3	1	2	*	2	2	21
Hall Beach	1	*	*	0	1	1	4
Houlman Island	2	3	1	*	1	2	17
Mould Bay	2	1	*	*	1	1	10
Resolute	4	2	2	1	1	3	29
Resolution Island	8	7	4	2	6	9	74
Sachs Harbour	1	*	*	*	*	1	6

* Average less than 0.5

Source: FENCO Arctic Atlas

Table 2.5 Average Number of Days with Gales (> 60 km/hr.) per Month and Year

Strongest winds in the Hudson Bay region occur in October and November, average 24 to 29 km/h. and prevail from a northwesterly direction. During the winter, wind speeds average 19 to 24 km/hr. with higher speeds over Hudson Strait and extremes of 80 to 100 km/hr. These wind speeds combined with low average temperatures create extreme wind chill factors.

In the upper part of the Labrador coast winds predominantly blow from a northwest direction throughout the year with mean wind speeds averaging 44 km/hr. in January and 25.4 km/h. in July. Winds predominantly blow from a westerly direction in the southern parts of the Labrador coast during January at an average speed of 23 km/hr. and flow from a southerly direction in July at an average speed of 20.6 km/hr. (Bursey et al. 1977).

Wind Effects on Ice

General Features of the Surface Velocity Field

The motion of the air in the middle regions of the troposphere derives directly from the gradients of the macroscopic pressure field and the effects of the rotation of the earth. At sufficiently great heights (say, in excess of 500 m over level country) the steady motion usually approximates to that given by the geostrophic balance. In the lower layers the motion is inevitably more complicated because of the distributing effects of the surface. In this region the wind is subjected to a frictional force whose magnitude varies with the nature of the surface and with the prevailing density distribution in the vertical. Additional complications arise from the appearance of local air currents unrelated to the main pressure field.

It is therefore advantageous to regard the air at these levels (a few tens of meters) as part of a fully developed turbulent boundary layer, in which both the Coriolis force and the changes in the gradient of pressure in the direction of the mean wind are negligible. If the temperature gradient is also small (as is the case over ice) throughout this lower layer, so that the air is of uniform density, the motion should resemble an idealized flow over a plane surface.

For a rough surface (most ice conditions) the velocity profile would be expected to conform to the following equation:

$$\frac{w}{w_*} = \frac{1}{\kappa} \ln \frac{z+z_o}{z_o} \qquad \text{Sutton (1953)}$$

Where κ = Von Karman constant, usually taken as 0.4
z = height of wind observation
z_0 = roughness length or turbulence length
w = observed mean velocity
w_* = shear velocity

The shear velocity may be expressed as

$$w_* = \sqrt{\tau_a / \rho_a}$$

Where τ_a = Wind Shear
and ρ_a = density of air
Substituting wind shear velocity into the general equation, the result is:

$$\tau_a = \rho_a \quad = \quad \left[\frac{x}{\ln \frac{z \times z_0}{z_0}} w \right]^2$$

This expression for shear force by wind on the ice sheet may be expressed by a contracted formula

or $\tau_a = \rho_a \, C_s w^2$

Where C_s = Wind shear coefficient = $\left[\frac{x}{\ln \frac{z + z_0}{z_0}} w \right]^2$

Wind Shear

The general formula which expresses the shear force which wind will exert on an ice sheet has been described on wind forces. Section 3.4.2.2

The shear coefficient depends on the roughness of the surface. As shown above, a logarithimic velocity distribution may be assumed to express the relationship.

Measured values of C_s and association values of z_0 are given in the table below along with a qualitative description of the roughness of the surface. The turbulence length z_0 could be related to Nikuradse sand roughness by

$$z_0 = \frac{k}{30}$$

where k is the roughness height.

If we assume:

$\rho_a = 1.4 \text{ kg/m}^3$

the range becomes

$$1.3 < \frac{\tau_a}{w^2} \quad 10^3 < 7.0$$

if w is in (m/sec)

and τ_a is in (Pa)

The values given for the drag coefficients are for a surface of uniform roughness. Ridges are usually a non-uniform feature that must be considered separately, as described by Michel 1978). Other values shown are from a review by Croasdale (Carstens 1980).

Height of Measurement m	Cs x 10^3	z_0 mm	Nature of Surface	Nikuradse Sand Roughness k in mm
10 (Air)	0.95	0.023	Smooth Snow Covered Surface (Michel)	0.7
10 (Air)	2.2		Average Rough Ice Cover (Danys)	
10 (Air)	2.61	3.98	Gently Rolling Hummocked (Michel)	120
10 (Air)	3.3	9	Rafted (Michel)	270
10 (Air)	5.0		Ridged Arctic Ice (Metge)	

The velocity of ice is usually small and ice can be assumed stationary, which corresponds to observations. The effect of ice shear is based on wind speed and ice velocity is neglected $(w - v = w)$.

Steady Wind from Drag on Floes and Icebergs

Wind drag on the sail of an ice mass or ice floe could be expressed as follows:

$P = \rho a \times Cdw^2$

where:

C_d = drag coefficient
P = pressure on the sail area of ice

Using a compound drag coefficient C_d the equation becomes:

$P = C_d \times \rho_a \times w^2$

and the force per unit width is an average conditions:

$F_d = 1.4 \times h_s \times w^2$ (N/m)
where h_s = sail height

2.2.1.5 Storm Paths

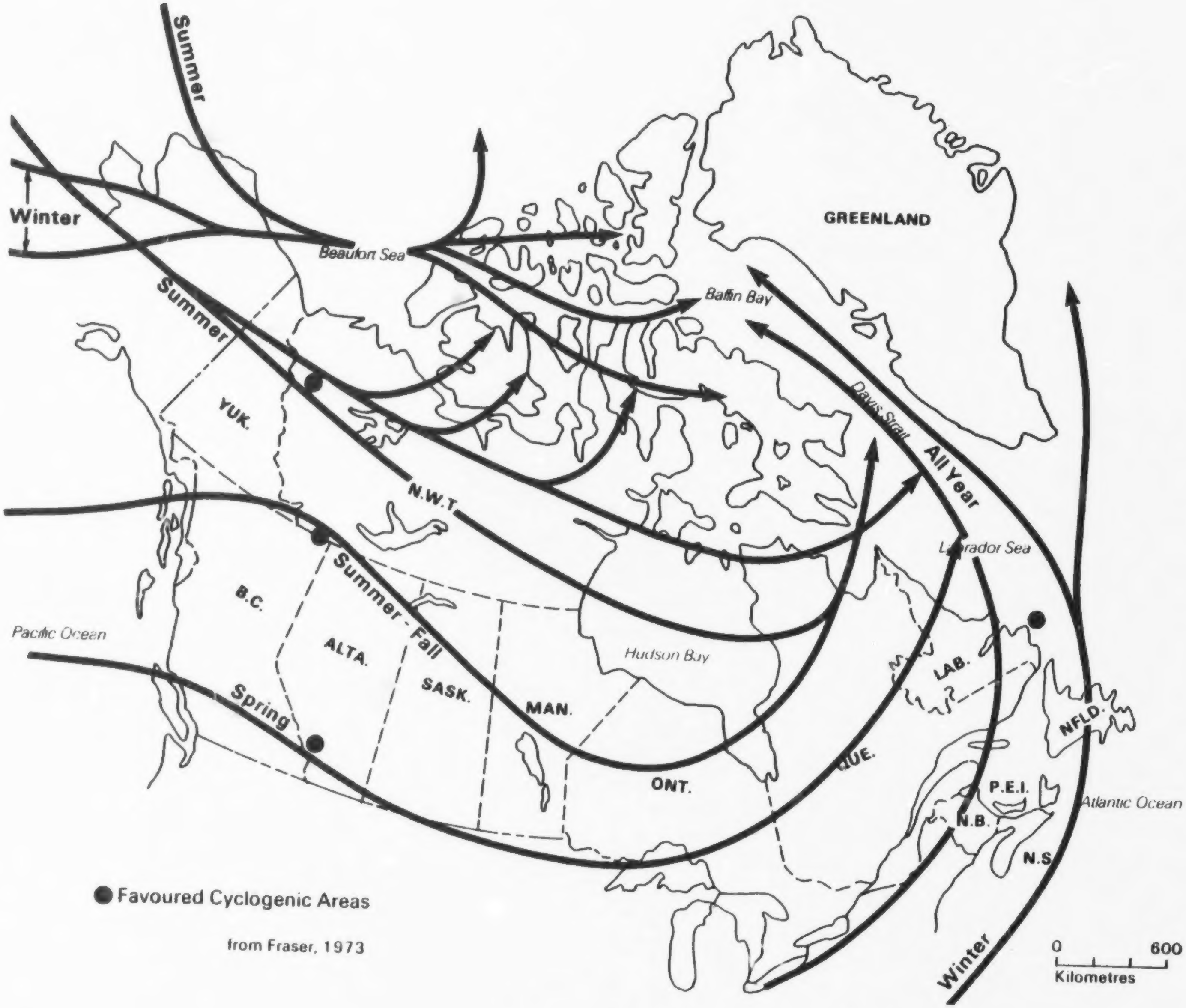
The Arctic Basin has as high a frequency of cyclonic activity as other areas during summer and winter, with a maximum in July. Generally speaking, low systems move from west to east and storm tracks spiral towards the pole.

In winter, short wave troughs can develop new surface centres in the Mackenzie Valley-Fort Nelson area which then move eastward on various tracks.

Frequent cyclogenesis is also initiated east of the Rockies in the Mackenzie Valley-Fort Nelson, Alberta and Colorado areas by Pacific short wave troughs as well as on the east coast in the Cape Hatteras-Cape Cod areas (see Figure 2.11). The tracks of these systems merge off the east coast and maintain the intense Icelandic low in winter. Baffin Bay is a dissipation zone for these lows that move directly north over the Labrador coast and through Davis Strait, and for others which are offsprings of lows crossing the southern tip of Greenland. Cyclones of Pacific and Hudson Bay origin often die in Baffin Bay and tracks into this area are much the same throughout the year. Storms approaching the Arctic Islands from the west most frequently penetrate from the Pacific via the Bering Strait during the months of December to February.

In the warm season, cyclones entering the Beaufort Sea near latitude 75N are important (see Figure 2.11), as are those that track east or northeast from the Siberian summer low in June and July. Those that develop in Alaska and the Yukon follow a rather zonal course into the Islands or Hudson Bay. In the spring and especially the fall, track west to east along 58N, 68N and 75N are active.

Strong meridional flow or blocking highs aloft can steer surface lows along unusual tracks in any season. Blocks over Hudson Bay or the central mainland create a southwest to northeast or south to north track, whereby lows of Pacific origin cross British Columbia then curve northward into the central Arctic. Strong blocks over Greenland can in


Summer
Winter
Beaufort Sea
GREENLAND
Baffin Bay
Summer
Davis Strait
All Year
YUK.
N.W.T.
Labrador Sea
B.C.
Summer - Fall
Pacific Ocean
ALTA.
Hudson Bay
LAB.
SASK.
MAN.
Spring
NFLD.
QUE.
ONT.
P.E.I.
Atlantic Ocean
N.B.
N.S.
● Favoured Cyclogenic Areas
Winter
0
600
Kilometres

from Fraser, 1973

Figure 2.11 Principal Arctic Storm Tracks

extreme cases create an east to west track over southern Greenland or Hudson Strait. Some of these track northwestward into the central Arctic in winter. A strong ridge aloft over Alaska may cause intrusion of warm air and cyclonic activity in the Mackenzie Valley even when the normal surface high is entrenched in the Yukon.

2.2.1.5 Humidity

A feature of the atmosphere in any cold climate and one particularly characteristic of the Arctic is its low water-vapour content. Because the water-vapour capacity of cold air is relatively low, water vapour added to arctic air quickly saturates it. A low, clinging "steam fog" is thus frequently seen suring the arctic winter over open water in the pack ice.

At temperatures of -37°C and colder, water vapour sublimates on hydrogen molecules and, as a result, a heavy blanket of "ice fog" is characteristic in the immediate vicinity of human settlements during very cold weather. Physiologically, the result of the low water-vapour content in the arctic air is that skin and nostrils quickly become, and are constantly - even painfully - dry. This is particularly true in heated buildings if no moisture is added.

2.2.2 Visibility Factors

2.2.2.1 Daylight

The Arctic Region has long periods of extreme daylight and darkness. The Arctic Islands represent the region with the most dramatic extremes (see Figure 2.12). At 75°N latitude, the location of Melville Island, periods of total darkness remain from the first week in November through to the first week of February, while continuous daylight conditions occur from May through to mid-August.

These extremes of daylight and darkness however, present only psychological barriers to continuous field operations. Work areas, in general, are organized, to allow for continuous work through the arctic night.

2.2.2.2 Visibility Restrictions

As the Arctic atmosphere is relatively free of impurities, the polar region exhibits characteristically high visibilities. Moreover, unusual optical effects caused by the bending of light rays under the Arctic inversion occasionally give abnormal extensions of the visual range. Of the conditions which restrict visibility, fog, ice fog and drifting snow are generally regarded as the most significant.

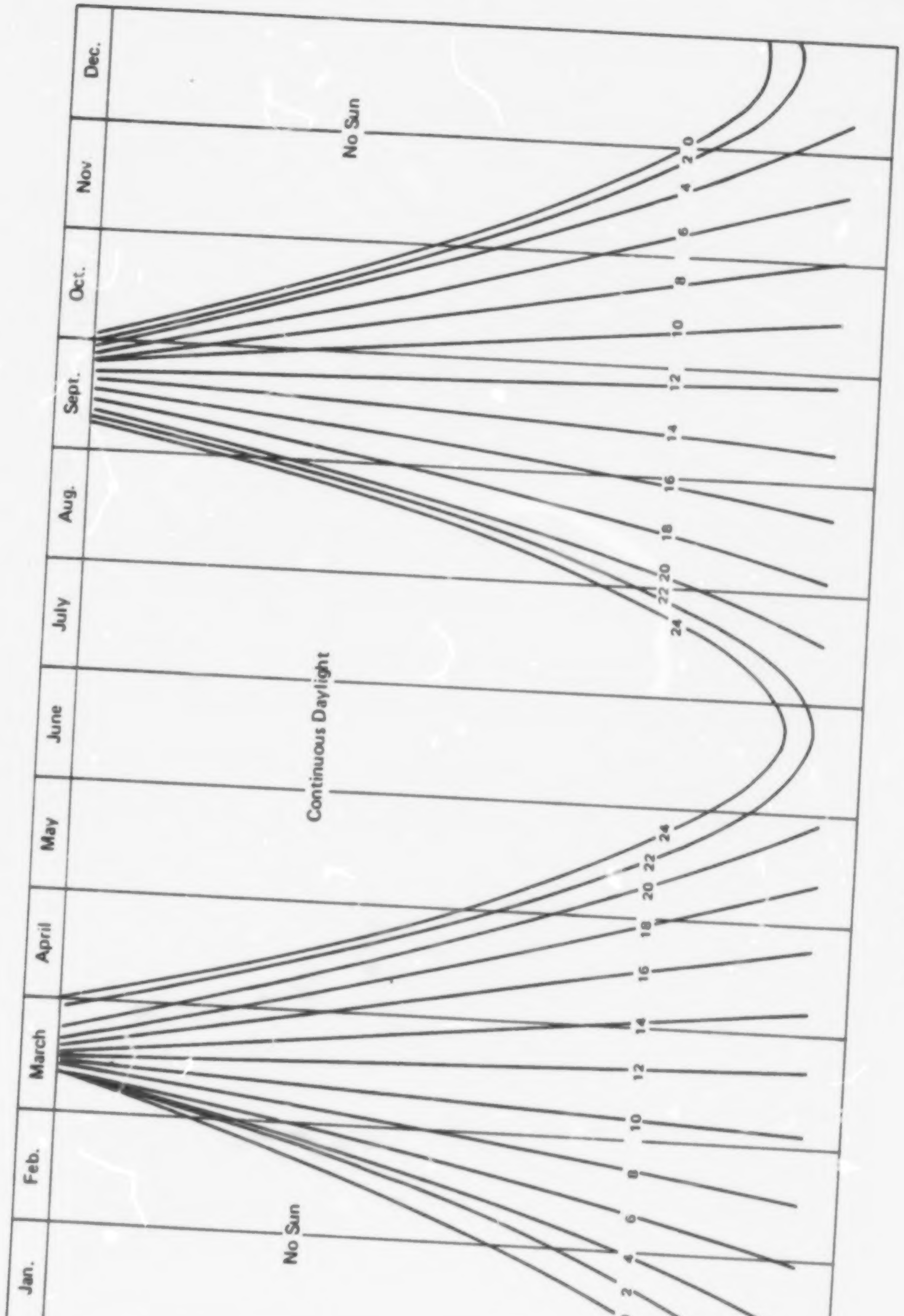


Figure 2.12 Duration of Daylight Relative to Latitude

Fog

During the period May to September advection type (sea) fog is a common obstruction to vision over the Arctic waterways and the Polar Basin (see Table 2.6). Throughout the regions even the warm air masses which penetrate from southern Canada are subjected to the cooling effects of extensive surfaces of ice-cold water. Evaporation from the exposed water areas and saturated ground surfaces produces a further cooling in the lower levels of the air mass. The resulting temperature inversion inhibits turbulent mixing with the drier air aloft. Beneath the inversion the air is moist and when it moves over colder water or drifting sea ice the excess moisture condenses to form fog or mist. Fog is widespread over the seas during the period when the ice is melting. As the season advances the fog becomes patchy, tending to be frequent and dense at the edges of the drifting ice and less frequent over ice-free seas and over land.

Advection fogs are quite dependent on the strength of surface winds and is more frequent over the seas when winds are light. While the layer of fog tends to be quite thick, it can effectively halt movement of aircraft and inhibit ground vehicle and marine traffic.

Steam fog forms when very cold air passes over areas of open water in winter. The rate of evaporation from the water surface remains relatively high in this situation while the capacity of air to hold moisture is restricted by its low temperature. The excess moisture in the air quickly condenses into fog. Steam fog is often observed in the Arctic during the period October to April, but it is relatively localized and usually does not persist more than a few miles downwind from the open leads or tide cracks. This fog may serve the purpose of informing the navigator of the presence of open water at a distance.

Ice Fog

Ice fog is largely a man made phenomenon in the Arctic, usually found in the vicinity of human habitation where large quantities of water vapour are added to the air through the burning of hydrocarbon fuels. Ice fog tends to form at low temperatures (usually below -25°C and most frequently below -35°C) when a low level inversion is present to trap and concentrate locally produced moisture in a shallow layer. While the occurence of ice fog is governed by local humidity, usually man made, the persistence and often the density is largely determined by atmospheric mixing, a function of wind speed and inversion strength.

	Years of Data	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
						Visibility 1 km or less								
Cape Parry	13	2.0	2.2	1.9	2.9	7.4	12.3	11.9	11.8	7.3	3.4	2.1	1.8	67.0
Sachs Harbour	15	0.8	0.4	1.0	2.7	7.1	9.7	14.5	13.7	7.9	3.9	2.1	1.9	65.7
Holman	24	1.3	0.8	0.6	0.4	0.9	2.5	5.2	3.6	1.5	0.6	0.4	0.2	18.0
Coppermine	30	0.6	0.8	0.5	1.8	2.8	3.6	2.0	2.1	1.8	0.7	0.7	0.6	18.0
Cambridge Bay	28	2.5	2.8	1.8	2.5	5.4	4.0	3.0	4.4	2.7	4.2	2.3	2.2	37.8
Spence Bay	16	1.7	1.1	0.6	1.0	2.2	1.8	2.6	2.4	1.4	2.2	1.3	1.3	19.6
Hall Beach	13	5.1	6.7	4.2	2.5	4.6	7.4	7.2	8.3	4.4	4.0	2.9	4.1	63.4
Mould Bay	23	1.5	2.0	2.8	3.0	3.1	2.6	2.7	5.8	5.2	3.5	1.3	0.9	34.4
Isachsen	22	1.4	1.9	4.4	3.9	3.4	4.5	6.1	7.6	8.5	5.3	2.6	1.4	51.0
Eureka	23	0.5	0.7	0.9	1.0	0.3	0.1	0.1	0.5	3.2	1.7	0.6	0.3	9.9
Alert	20	0.8	0.5	0.8	0.9	5.7	6.9	7.0	8.9	6.5	3.5	2.0	0.6	44.1
Resolute	23	1.9	2.8	2.7	1.8	3.3	7.4	9.8	9.4	4.6	2.6	1.3	1.2	48.8
Arctic Bay	25	0.3	0.2	0.6	0.7	1.1	0.4	1.4	1.4	0.4	0.4	0.2	0.2	7.3
Clyde	15	0.7	0.9	0.7	1.3	2.7	3.0	4.8	5.0	1.1	0.9	1.1	0.7	22.9
Cape Dyer	12	4.5	5.4	2.7	1.9	12.1	11.8	8.5	10.7	8.6	8.2	5.0	3.4	84.8
Frobisher														
Nanisivik														
Deception Bay														

Source: Fenco Arctic Atlas

Table 2.6 Average Number of Days with Fog

Blowing Snow

At many Arctic locations, blowing snow is the most frequent cause of poor visibility. This is particularly true in winter when the ground is covered with fresh, loose snow. At wind speeds as low as 10 km/h., fresh snow begins to move or drift and at speeds of 20 to 30 km/h., is swept in the air in sufficient quantity to reduce the visibility close to the ground. Table 2.7 shows the average relationship between wind speed and visibility at Resolute, N.W.T.

Wind Speed (km/h.)	<24	24	32	40	48	64
Visibility (km)	10	5-10	2-5	1-2	1	Near Zero

Table 2.7 Wind Speed and Surface Visibility at Resolute, N.W.T.

The wind speed at which snow begins to drift depends on snow density and hardness. A fresh snowfall will drift easily, with higher speeds required to move snow as the snow surface "packs" or hardens. Once the snow surface has acquired the characteristic hardness appropriate to the prevailing wind, drifting subsides and visibility improves. If there is a wind of 65 km/hr. for 3 days following a fresh snowfall, the visibility typically is zero the first day and begins to improve to about 1 km the second and to 6 to 7 km or so at the end of the third day.

Blowing snow associated with high winds can ground air traffic, often for days at a time. The low visibilities encountered with blowing snow also makes vehicular traffic dangerous. Drifting snow can cover a road within a few hours. Blowing snow is difficult to forecast and often occurs suddenly. A clear cold day with unlimited visibility can change to near zero visibility within a few hours.

The low visibility conditions in the Arctic are greatly accentuated by white out conditions, especially in spring and fall with the sun near the horizon, a uniform snow cover, and a stratus overcast. Under such conditions, the observer loses all sense of depth perception, and aircraft and other operations can become difficult and dangerous.

Generally, the first problem evolving from low visibility is the restricted movement of aircraft. Such a problem is of great concern for the effective transportation of men and materials during winter operations and construction projects when marine shipping routes are not available.

2.2.3 Snow Loads

Most of the Arctic regions receive an average annual snowfall which ranges between 50 to 125 cm and exhibit a pattern of reduced precipitation with increased latitude. Maximum snow loads in the Sub-Arctic regions occur in the Labrador Sea area, where mean yearly snowfall averages 3.23 m. Snow loads of 3 m would result in pressures on a structure of less than 7 kPa. As the snow loads are so small, they are not considered an important criteria in the design of offshore structures. The effects of drifting snow should, however, be taken into consideration when assessing loads on floating ice platforms.

2.2.4 Superstructure Icing

Superstructure icing creates a load on a vessel above the water line which elevates the centre of gravity, increases the heeling moment due to wind action and, in extreme conditions of high winds and low air and water temperatures, can cause a vessel to capsizing.

There are three main types of icing which may result in ice accumulation on the hulls and superstructures of ships moving through the Arctic, namely freezing rain, freezing spray and ice fog. For freezing rain to occur, surface temperatures must be at or below freezing (0°C) and an inversion must be present, i.e. there must exist aloft a layer of air with above freezing temperatures. The type of freezing precipitation that will be produced at the ground will then depend on the extent of the layer with above freezing temperature, as well as on the depth of the underlying cold air (Gardner 1978 - Vol. 2, Appendix 2).

Freezing drizzle may occur, however, without an upper layer with above freezing temperatures. The only requirement is that there be a long and sustained fetch of cold moist air trapped beneath an inversion (Gardner 1978 - Vol. 2, Appendix 2).

Frequencies of freezing precipitation in the Arctic are quite low and confined usually to the September-October period when occurrences at most stations average less than 25 hours. Only along the exposed southeast coasts of Baffin Island and in the open waters off the Labrador-Newfoundland coast is this type of ice accretion a hazard to modern shipping.

Several investigators have studied the relationship between accretion rates and meteorological parameters. Kuroiwa (1965 - Vol. 2, Appendix 2) developed analytical expressions to compute radial ice accretions on wires. Power et al. (1972 - Vol. 2, Appendix 2) showed that wind direction was an important factor in glaze accretion. His findings suggested that cylinders exposed at right angles to the prevailing storm winds accreted maximum glaze amounts. The concept of orientation as a factor in ice accretion seems to be confirmed by the work of Chaine and Skeates (1974 - Vol. 2, Appendix 2)) who computed ice accumulations on horizontal and vertical surfaces due to freezing precipitation. Their results for Sable Island, based on extreme value distributions indicate that ice accumulations on vertical surfaces exceed those on horizontal surfaces by a factor of about 3.

Table 2.8 gives accumulation rates for stations at Cape Parry and Sachs Harbour.

	Return Period in Years							
Station	2	5	10	15	20	25	50	100
Cape Parry	11.4	11.8	22.4	24.9	26.6	28.0	33.5	36.2
Sachs Harbour	27.3	26.0	31.8	35.1	37.4	39.1	44.6	49.9

Table 2.8 Return Period of the Maximum Amount of Ice in cm that Would Accumulate in One Storm.

Freezing precipitation presents a significant hazard to aircraft operations and surface transportation systems, as well as to surface based structures such as towers and transmission lines (McKay et al. 1969). Fast moving cyclones, stationary or slow moving fronts, blocking patterns which develop sustained onshore flows, sharp cold fronts that produce rapidly falling temperatures, and strong winds following periods of wet snowfall, may all lead to dangerous buildups of ice and snow on towers, transmission lines, and other structures under appropriate conditions (Gardner 1978 - Vol. 2, Appendix 2).

The second type of icing occurs in fog at below freezing temperatures or in steam fog. In certain areas of the north Atlantic this type of icing can be dangerous to shipping but in the Canadian Arctic where the moisture source is cut off as the seas quickly become ice covered in the fall, the problem is not serious.

In strong or gale-force winds the spray coming over the bow freezes on the ship's superstructure if the air temperature is lower than the freezing point of salt water. Severe storms, when both air and water tempertatures are low, produce severe icing. With the exception of the Labrador Shelf, Baffin Bay and Davis Strait, where large areas remain free of ice until well into the winter, the season where this type of superstructure icing would occur in the Arctic is pretty well limited to the months September to November. Even small concentrations of ice floating on the sea surface will dampen waves considerably, and concentrations greater than about seven tenths will mostly eliminate waves. The edge of the ice field acts as a coastline and the short fetch between the ice and ship is not sufficient for the wind to develop the waves fully. Thus the period when spray icing can be a problem in the Arctic is rather short.

The principal risk involved in the icing of ship superstructures is loss of stability. Continued accretion effectively lowers the metacentric height, thus changing the vessel's period of roll and critical heeling angles, adversely affecting seaworthiness, manoeuverability, and possibly leading to capsizing (DeAngelis 1974 - Vol. 2, Appendix 2).

Icing on vessels of varying sizes has been reported by various authors, (Vol. 2, Appendix 2) notably Stallabrass (1971), Mertins (1968), Borisenkov et al. (1974) and DeAngelis (1974). Shellard (1974 - Vol. 2, Appendix 2) wrote a comprehensive report on world wide ice accretion on ships for the World Meteorological Organization. Stallabrass (1980) collated and reviewed the results of an eleven year study on the icing of fishing trawlers off the Canadian east coast.

Most authors seem to be in general agreement on the causes of ship icing (Hay 1956, Tabata et al. 1968, Borisenkov et al. 1974, Dacam 1970, Stallabrass 1971, Smail 1971 - Vol. 2, Appendix 2). Supercooled fogs, freezing rain, freezing drizzle, and wet snow are all categorized under freshwater icing, and are not considered to cause any serious ship icing. Saltwater icing, however, caused by either vessel or wind generated freezing spray, is considered to be the principal and most dangerous cause of ship icing. Borisenkov et al. (1974) and Shekhtman (1971 - Vol. 2, Appendix 2) in analysing 2000 cases of icing on fishing vessels reported that in 90% of the cases the cause was freezing spray.

There is also general agreement regarding specific meteorological and oceanographic factors that result in freezing of sea spray on ships (Borisenkov et al. 1974, Dacam 1970, Vasil'yeava 1967, Skekhtman 1971 - Vol. 2, Appendix 2). Air temperatures must be below the freezing temperature of seawater (about -1.8°C depending on salinity); sea temperatures should be below +6°C; wind speeds should be in excess of 20 knots, although at lower wind speeds slight icing is possible.

Synoptic conditions that favour the generation of freezing spray are also generally agreed upon. The passage of a well developed low pressure system through the areas, or the formation of a closed stalled low off Labrador will both produce conditions of potential icing hazard (Stallabrass 1971).

The size and lines of the vessel, including free board, amount of rigging and other obstructions above-deck, as well as the ships speed and relative heading, are other important factors in the accretion process (Stallabrass 1980).

Because of the many variables, some of which are not easily measured, the prediction of the rate of accretion due to freezing spray is difficult. The best that can be done is to indicate the probable severity of icing, in rather broad qualitative terms and, consequently, predicted severities should be treated as rough approximations.

Towards this end certain empirical approaches have been devised. Correlation diagrams relating air temperature, wind speed and, in some cases, sea temperatures, to icing severity, have been developed, notably by Sawada (1962), Mertins (1968), Comiskey (1976) and Stallabrass (1980 - Refer to Vol. 2, Appendix 2). Figure 2.13 is a nomogram currently in use by AES forecasters in Eastern Canada, and is adapted after Sawada (1962). An in-depth study on icing on semi-submersible rigs on the Hibernia field was conducted by NORDCO in 1981. All reported cases of icing were matched with prevailing weather conditions. Drawing from previous work by Minsk (1977 and 1980 - Vol. 2, Appendix 2) and using the model developed by Mertins in 1968, estimates were made of the accummulation rates, weight of icing and its effects on rig stability. The study concluded that under the worst conditions expected in the area, the combination of sea spray and precipitation icing might reach a maximum of 830 tonnes. This degree of icing would cause no significant loss of stability to a semi-submersible rig, but would limit the performance of support vessels, operation of rig machinery and create a hazard for personnel. The results of this study give some indication of the extreme limits of platform icing which could be experienced in Eastern Canada (NORDCO 1981 - Vol. 2, Appendix 2).

There are essentially two types of ice accumulation: rime ice and glaze ice. Of the two, glaze icing formed from the slow freezing of large super cooled drops represents the most dangerous as a result of high density and adhesion strength. (Adhesion strength of various materials is presented in Chapter 3.) Shekhtman (1968) found that rapid ice accumulation occurred from sea spray with air temperatures -2°C and wind speeds 10 m/sec.

A study completed at Cape Parry and Sachs Harbour adjacent to the Beaufort Sea, from data collected in September and October over a 13 year period, indicated that a storm with an ice accumulation of greater than 10 cm thickness will have a return period of two years, and thicknesses double this amount are expected to recur every 10 years (see Table 2.8).

2.3 Oceanography

The Ocean Information Division of the Institute of Ocean Sciences (IOS) Sidney, B.C., under their Ocean Information & Data Services Program, maintains and regularly updates all oceanographic data for the Canadian Arctic. The information is archived in a computer data base, thus permitting a quick search and retrieval of data sets pertaining to times and location of measurements for temperature, salinity, currents, water levels, for the Beaufort Sea, Arctic Islands, Baffin Basin, Davis Strait and Hudson Bay regions.

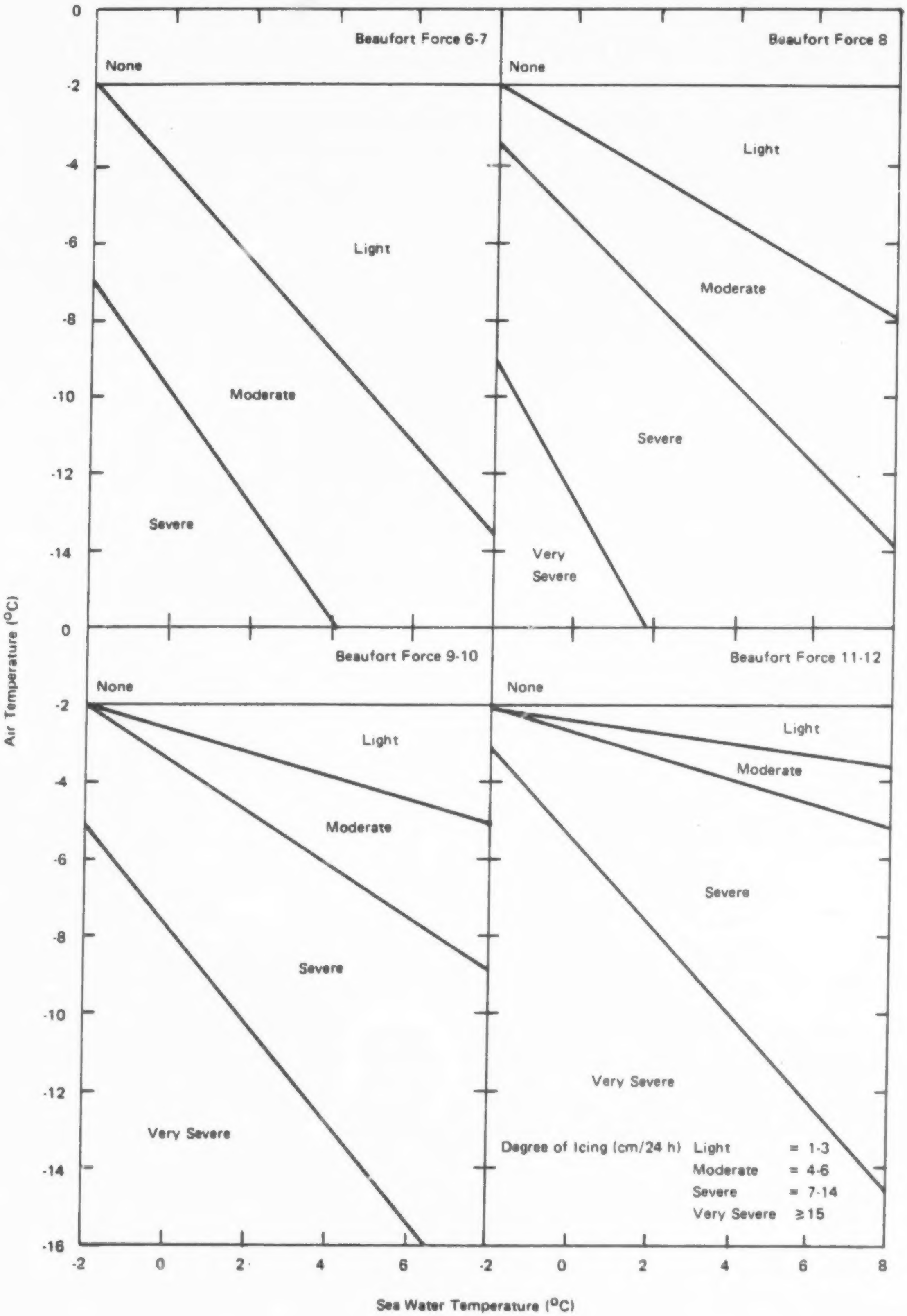


Figure 2.13 Icing Diagram (From Mertins, 1968)

The Institute publishes a series of catalogues containing the available data. A description of catalogues available are presented in Table 2.9.

Site specific investigation of oceanography is required for the design of marine structures. The following, therefore, is a general description of the physical oceanographic characteristics that are encountered in the Canadian Arctic regions.

2.3.1 Sea Water Characteristics

The water characteristics, temperature and salinity of the Canadian Arctic is largely dependent upon the global water masses and circulation in this region. A brief description follows:

The Parry Channel system including Lancaster Sound, Barrow Strait, Viscount Melville Sound and M'Clure Strait forms a zone of transition between the waters to the west, characteristic of the Arctic Ocean, and those to the east that are formed through an interchange of Arctic water with that of the West Greenland and Baffin Bay waters (i.e. north Atlantic waters). The western water, which extends from the Beaufort Sea to M'Clure Strait is identical in physical properties to that which has been described farther off-shore in the Arctic Ocean. As this water moves into the Canadian Arctic Archipelago only water of the surface layer (0-150 m) can pass eastward over the sill into Lancaster Sound. In Lancaster Sound the temperature and salinity characteristics at depth are determined by the relative contributions of waters of Baffin Bay and the Arctic Ocean.

A comparison of the temperature-salinity relationships for Arctic Ocean and Baffin Bay shows that the upper waters of the Arctic Ocean are much less saline than those found in Baffin Bay, the minimum temperatures are similar (-1.8°C) in the upper 200 m. Below this level the Arctic Ocean waters are of higher density than that found at corresponding depths in Baffin Bay.

2.3.2 Currents and Circulations

Generally, ocean waters move in a variety of quasi-periodic ways, frequencies vary from those belonging to molecular motion and Reynold's stress to those related to long-period changes in climatic weather conditions. The space-scales which apply to these movements also vary enormously, from molecular distances to the length and width of the ocean. It follows that when current measurements are made at any point in the ocean, the vector sum of all spectral components of the currents in the area will be recorded. Thus, in order to properly interpret and apply a current record to marine structural design, it is essential that the relative contributions of various current components be properly determined. Harmonic analysis of the record is usually made for this purpose (Godin 1972). However, the accuracy of this analysis is strongly limited by the length of the record. The mechanism by which

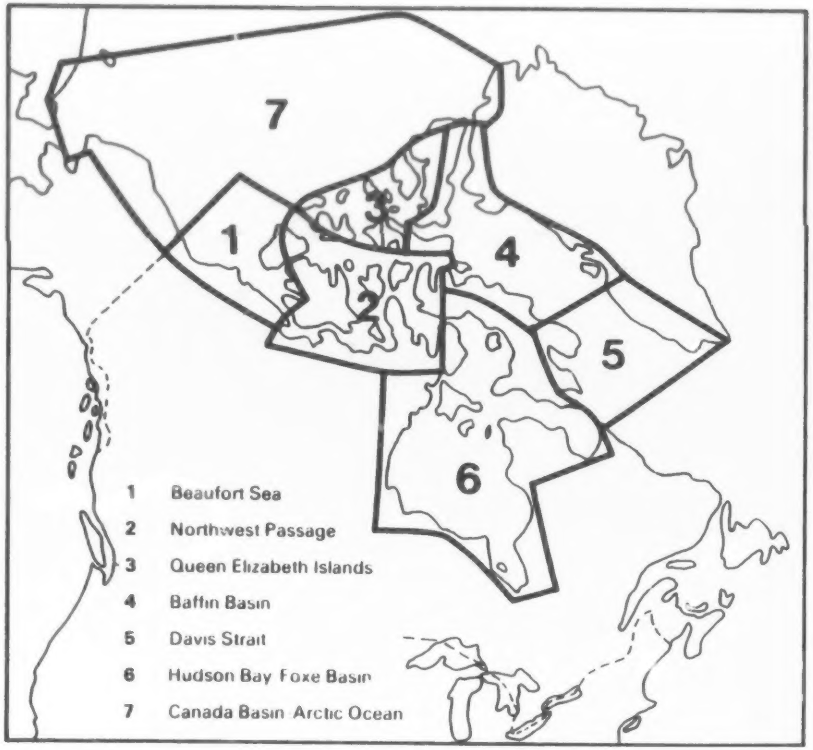


Table 2.9 Description of Catalogues Available

Arctic Data Program

Ocean Information Division
Institute of Ocean Sciences
Sidney, B.C.

Phase I: **Data Compilation and Appraisals**

Geographic Area	Title/Description	Status	Publication Date
1	Beaufort Sea: Physical Oceanography – temperature, salinity, currents and water levels	Completed	October 1982
1	Beaufort Sea: Chemical Oceanography – nutrients, metals and hydrocarbons	Completed	March 1983
1	Beaufort Sea: Biological Oceanography – whales	2nd Draft Completed	August 1983 (projected)
1	Beaufort Sea: Biological Oceanography – zoobenthos	1st Draft in prepar.	October 1983 (projected)
1	Beaufort Sea: Biological Oceanography – marine and andromous fishes	2nd Draft in prepar.	August 1983 (projected)
2	Northwest Passage: Physical Oceanography – temperature, salinity, currents and water levels	Completed	April 1983
2	Northwest Passage: Chemical Oceanography – nutrients, metals and hydrocarbons	1st Draft Completed	August 1983 (projected)
3	Queen Elizabeth Islands: Physical Oceanography – temperature, salinity, currents and water levels	2nd Draft in prepar.	August 1983 (projected)
4	Baffin Bay and Ellesmere Island: Physical Oceanography – temperature, salinity, currents and water levels	2nd Draft in prepar.	August 1983 (projected)
Phase II:	**Adequacy of Existing Data for Environmental Assessment**		
1	A chemical mass balance of the Mackenzie Shelf: natural and anthropogenic sources of hydrocarbons, heavy metals and sediments	2nd Draft in prepar.	July 1983 (projected)

each component of the current spectrum is generated (i.e. the driving force) should be determined, this being of greater importance to an overall understanding of local current regime. This mechanism is very complex, particularly in the ocean, due to the interaction of many different forces and current regimes, i.e. tides, winds, pressure gradient, geostrophic forces (i.e. coriolis forces), barotropic flow (due to sea level differences) and baroclinic flow (due to horizontal mass differences).

The general flow characteristics (i.e. large scale circulation), velocities and typical components of currents in the Arctic regions are summarized below.

a. Tidal Flow

In most areas in the arctic, tidal flow (mainly semi-diurnal and diurnal constituents) dominates the current regimes (see Section 2.3.3). The tides are generated by two different tidal waves; the first one propagates from the arctic and the second from the Atlantic Ocean. Tidal ranges diminish as each tide propagates into the archipelago.

If generated by a single standing or progressive tide wave, tidal currents in open water are alternating, but when the earth's rotation is considered, tidal currents become rotary (clockwise in the northern hemisphere). Near-shore measurements, of course, usually show alternating currents, because of boundary effects.

In open water, disregarding the rotation of the earth, the maximum tidal current velocity, V_m, is given by

$$V_m = \sqrt{g/h}\ A$$

where g is the acceleration due to gravity, h is the water depth and A the tidal amplitude.

b. Long-Period Flow

Long-period water flow may be generated by a variety of mechanisms. Firstly, sea level differences may occur due to large-scale circulations of adjacent oceans and due to atmospheric conditions. Both conditions may create barotropic flow while abnormal conditions may create surges (see Section 2.3.5). Apart from boundary effects, barotropic flow is uniform throughout the entire water column.

Secondly, baroclinic flow may be generated by horizontal mass differences within the ocean. As long as these differences are maintained, the flow will remain steady for indefinite periods.

c. Wind-Induced Flow

The water in the arctic regions is usually not subjected to wind stress due to ice cover. However, when the ice breaks up, significant wind-induced currents may be generated. The strength and direction of these currents depends on the wind characteristics and fetch length. As a general rule of the thumb, the velocity of the surface currents is typically about 2% of the wind speed and direction 45° to the right of the wind stress vector. As the velocity decreases, the direction changes with water depth (i.e. Ekman spiral). Since wind in the High Arctic is predominantly from the north-west, wind driven surface currents are predominantly, southwesterly.

d. Seiche-Induced Flow

As in lakes, standing waves may be generated in basins having an appropriate geometry. The period of these waves is determined by the geometry of the basin. The surface currents which may be generated in this way can be quite significant.

e. Internal Wave-Induced Flow

When the water is highly stratified, it is likely that internal waves are common. These waves, characterized by periods ranging from several minutes to several hours, generate subsurface currents which are often strong, especially at the internal boundary.

f. Wave-Induced Currents

Littoral currents and their associated longshore and rip currents are caused by waves breaking at an angle to the coastline. As sea waves approach shoaling water, they become waves of translation and pile up water against the coast. A hydraulic head is thus established and cause longshore currents to be created. Littoral currents and processes are of great importance in shoreline protection and certain coastal engineering problems (U.S. Army Shore Protection Manual).

General Current Circulation in Arctic

The major currents affecting the arctic waterways have not been measured quantitatively, but it is known that relatively warm water flows northward along the Greenland shore and crosses to the Canadian side at the north end of Baffin Bay where it mixes with a southward-moving cold current from Nares Strait. The resulting cold current flows southward along the Baffin coast, having received a minor cold outflow from Jones Sound and a more significant one from Lancaster Sound in passing. The rate of this motion is near 40 cm/sec off the northeast coast of Baffin Island, but there is little accurate information, even in summer, and virtually none for other seasons.

In the Arctic Ocean, a gentle clockwise, water circulation has been identified in the sector between North America and the Pole with its centre at about 80°N, 160°W. Part of this Arctic ocean circulation passes through Beaufort Sea. The southward flow towards Ellesmere Island is the source of the cold current through Nares Strait referred to above. Through the remainder of the waterways there tends to be a southward drift among the Queen Elizabeth Islands and an eastward flow through Parry Channel. Water motion around Victoria and Prince of Wales Islands is very limited, for the only exit of any significant width is westward along the continental coast and even this is shallow, island-studded areas. Similarly, southward flow through Prince Regent Inlet is limited by the small cross-sectional area of Fury and Hecla Strait.

The many narrow bodies of water surrounding the Arctic Islands are also subject to various other local characteristics due to wind-generated currents. The process involved here is one in which wind blows over the water surface creating a stress on surface water particles which in turn start moving in the direction in which the wind is blowing. When the surface current thus created reaches a barrier, such as a coastline, water tends to pile up against the land in what is known as a wind setup (or storm surge in the case of large bodies of water).

The actual height depends on wind velocity, fetch, water depth, and nearshore slope. Converging channels may increase the magnitude of such setups or surges due to their funnelling effect.

The circulation in Hudson Bay was described by Dunbar (1951) Collin and Dunbar (1964) and Hachey (1954). In general, the circulation is counter-clockwise with a southward flow on the west side and a northward flow on the east side of the Bay.

The waters flowing eastward through Hudson Strait originate in Hudson Bay and Foxe Basin. As these waters proceed toward the east they tend to be confined to a thinner surface layer and finally lose their identity as they reach the waters of the open ocean. A strong segment of the Labrador Current enters Hudson Strait along the Baffin coast by rounding Resolution Island and also by passing through Gabriel Strait. According to Smith (1931) icebergs have been carried westward by this flow for a distance of 150 miles where, near Big Island, they nearly all recurved and drifted eastward past Cape Chidley.

From a more extensive investigation of the oceanography of Hudson Strait, Campbell (1958) concluded that the dominant feature of the circulation is an eastward movement along the coast at a rate of 8 to 17 cm/s (0.15 to 0.34 kt). The velocity of this discharge as it passes through the eastern end of the channel is calculated to be 15 to 21 cm/s (0.3 to 0.4 kt).

The general current circulation in Baffin Bay and Davis Strait is caused by the Gulf Stream, and the cold, less saline water of the East Greenland Current (arctic water), which originates from the Arctic Ocean and meet near the southeast coast of Greenland. These two masses of water then jointly flow northwards along the west coast of Greenland as the West Greenland Current. Between latitudes 60°N and 67°N, branches of the West Greenland Current flow across Davis Strait and join the south-moving Labrador Current. In Baffin Bay, the main current follows an anti-clockwise circulation north along the Greenland coast to Melville Bay, crosses Baffin Bay to Baffin Island and then turns southwards as the Baffin Current. Some current also branches across central Baffin Bay and joins the south-moving Baffin Current (U.S. Coast Guard Oceanographic Reports 1968, 1969; Collin and Dunbar 1964; Muench 1970; Arctic Pilot Project).

The circulation in Baffin Bay plays an important role in the drift of icebergs from their parent glaciers on the western Coast of Greenland to the North Atlantic shipping lanes off the Grand Banks (IIP reports 1914-1983; Murray 1969; Markham 1981). The southward flowing, relatively cold, Baffin Land current along Baffin Island and recirculation of some West Greenland Current Water through the western side of Davis Strait account for the outflow of water from Baffin Bay. A portion of this flow enters Hudson Strait and follows the anti-clockwise circulation in Hudson Bay. The Labrador current is then formed at the junction of Baffin Current and the cold circulatory current from Hudson Strait.

The current flow along the Labrador coast has a strong spatial variability dependent on bottom bathymetry (Section 2.1) and different water masses. There are two distinct southward transports, usually referred to as the inshore and offshore streams. The inshore stream is located inside the Banks following the contours of the Labrador Marginal Trough and the offshore stream is located at the shelf break. The currents on the Banks are weak and variable, while the currents in the saddles are strong and produce a cross-shelf transport (west-east direction).

The waters of the Labrador current come from different sources. The water on the shelf in the top 150 metres comes from the Baffin Current and Hudson Strait while the warm more saline on the slope and in the saddles comes from the west Greenland current.

The major portion of Labrador Current continues south-eastward along the east coast of Newfoundland to the north slope of the Grand Banks, where it divides into three branches (Petrie and Anderson 1983): western branch flowing around the Avalon Peninsula, the middle branch following the eastern edge of the shelf through Flemish Pass, and the eastern branch flowing to the north of Flemish Cap.

Current Forces

Currents at a particular site can contribute significantly to the total forces exerted on the submerged parts of a structure. In addition, they generally present other adverse functional effects, such as scouring, deposition, increased corrosion rates, modification of wave effects, drifting of ice sheets, ice islands and icebergs.

Currents are essentially a horizontal movement of water that arises from various sources as described previously. Large-scale ocean surface currents are generally caused by major wind systems and are responsible for large scale drifting of sea ice and icebergs. Deep-running sea bottom currents are associated with density differences. There are also the more localized tidal currents (see Section 2.3.3), wind stress currents, hydraulic currents, turbidity currents due to submarine landslide, density gradient or stratified flow, wind-setup and storm surges currents (see Section 2.3.5). Of the above, tidal currents and storm-related wind-driven currents are of the greatest concern in marine structural design. All currents are modified by the earth's rotation, i.e. Coriolis forces, friction and boundary conditions. Currents range in velocity from few cm/s for major ocean currents as shown previously to several m/s for localized tidal currents. For more details on above types of currents and their effect on the structural design refer to U.S. Army Shore Protection Manual (1973); Wiegel (1964); Gaythwaite (1981).

Current Design Guidelines

Current design criteria should be selected in accordance with the importance of the structure and its sensitivity to current loads. The most important single factor in designing for current loads is the selection of the maximum design velocity. This selection should be based on actual measurements when possible or on a reliable source of data. Consideration must be given to seasonal or storm water levels and superposition of various interacting sources of currents. Statistical analysis of a given set of data (measurements) may be performed to determine the design current velocity for a given probability of occurrence or return period. The vertical distribution and in the case of rivers and narrow channels the horizontal variations of current velocity must also be considered. The seasonal maximum spring tide current should be selected for the design tidal current velocity, which is usually 10% to 20% greater than the average tidal current.

In general, for shallow water sites where measurements are lacking the vertical distribution of tidal current velocity is determined by (Gaythwaite, 1981 - Vol. 2, Appendix 2):

$$U_{TZ} = U_{TS}\,(Z/d)^{1/7} \qquad U_{TZ} = U_{TS}\,(Z/D)^{1/7} \qquad (2.3.1)$$

where U_{TZ} = current velocity at distance Z above bottom

U_{TS} = surface current

d = water depth

The tidal current profile should be added vectorially to the maximum wind-stress current, which can conservatively be assumed to be linearly distributed from maximum at surface to zero at the bottom.

The current velocities from other sources (wave-induced, storm surges, etc.) should also be added vectorially to produce the design current velocity (U).

Current forces on marine structure can be divided into:

- drag force (F_D)
- lift force (F_L)
- inertia force or mass force (F_M)

The drag force, acting in the flow direction, is due to shear stress or friction between the fluid and the body. It depends on fluid viscosity, the body shape and surface roughness.

The lift force (F_L) is due to the eddy (or vortex) shedding. It is hydrodynamic force acting perpendicular to the current direction and oscillating with time. Such forces may be of critical importance in the case of long slender cylindrical components (such as piles) placed in steady high velocity stream, and may be responsible for exciting harmonic motions which may require special treatment.

The third current force is due to the dynamic forces that arise from accelerating the mass of fluid on a submerged body. Slender and flexible structures are the most susceptible to dynamic enhancement which depends on the structure's natural period of oscillation, to the periodicity of the force and the degree of damping in the system (Timoshenko and Young 1954).

The drag, lift and inertia forces can be expressed as follows (Morison et al. 1950; Wiegle 1964; Gaythwaite 1981), assuming a uniform current velocity in vertical and horizontal directions.

$$F_D = \frac{1}{2} C_D \rho |u| u \quad A_p \qquad (2.3.2)$$

$$F_L = \frac{1}{2} C_L \rho u^2 \quad A_p \qquad (2.3.3)$$

$$F_M = C_M \rho \frac{dv}{dt} \quad A_0 \qquad (2.3.4)$$

where:

u = total horizontal water particle velocity vector calculated as if the body were not there

C_D = drag coefficient

C_L = lift coefficient

C_M = inertia or mass coefficient

ρ = density as fluid

$\frac{dv}{dt}$ = total horizontal water particle acceleration

A_p = projected area exposed to the flow

A_0 = Area of virtual mass of fluid that moves with the object ($= \pi D^2/4$) for a cylinder where D is the diameter).

The Drag coefficient for a wide variety of shapes and structures are given in the U.S. Navy Design Manual (1970) Gaythwaite (1981).

Based on the compilation of information collected from several studies, the Coastal Engineering Research Centre of the U.S. Army (1973) suggested the following values of C_D and C_M for given values of Reynolds number Re (for piles):

Drag coefficient C_D:

$R_e < 2 \times 10^5$, $C_D = 1.2$
$2 \times 10^5 < R_e < 5 \times 10^5$, $C_D = 7.86 - 1.26 \log_{10} R_e$
$R_e > 5 \times 10^5$, $C_D = 0.7$

Inertia Coefficient C_M:

$R_e < 2.5 \times 10^5$, $C_M = 2.0$
$2.5 \times 10^5 < R_e < 5 \times 10^5$, $C_M = 2.5 - R_e/5 \times 10^5$
$R_e > 5 \times 10^5$, $C_M = 1.5$

As indicated above, C_M decreases with increasing R_e, however, for small Reynolds numbers (i.e. $R_e < 3 \times 10^4$), the Keulegan-Carpenter parameter K_c plays an important role in determining C_M (for $K_c < 1$, $C_M = 2.0$)

where

$R_e = \frac{vD}{\eta}$ (η is water viscosity)

$K_c = vT/2\pi D$ (where T is wave period)

In addition, Gaythwaithe (1981) indicated that the drag coefficients also vary with the aspect ratio λ (i.e. the ratio of width to length) as follows:

For square plates normal to the direction of flow ($\lambda = 1.0$), $C_D = 1.12$; for rectangular plates with $\lambda = 5$, $C_D = 1.2$; for $\lambda = 20$, $C_D = 1.42$; and at $\lambda = \infty$, $C_D = 1.98$.

Example:

The total force in flow direction on a cylinder of length L and diameter D placed in water current with variable speed V at a given instance, can be expressed as the summation of drag and inertia components by the equation:

$$F(t) = {}_0\int^L \tfrac{1}{2}\, C_D\, \rho\, D|v|v \;\; dL + {}_0\int^L \rho \left(\frac{\pi D^2}{4}\right) \frac{dv}{dt} dL$$

where F(t) is the instantaneous force at time t, v and dv/dt are velocity and acceleration of water particles at the centre of the cylinder.

For steady flow (i.e. constant velocity), the second term in the above equation will be zero.

The current forces on an ice sheet, ice flow, or iceberg is mainly due to the drag forces (equation 2.3.2) between water and ice body.

Due to the great depth of larger icebergs, the currents velocity must be depth integrated to study the forces on the berg, in particular, wind driven Ekman transport.

2.3.3 Tides

Tidal variations are due to the continually changing distances of the sun and the moon from the earth and their positions relative to it. Various types of tidal data for the Arctic regions are available in the latest "Canadian Tide and Current Tables" (Dept. of the Environment); however, a few comments about the general pattern are given here.

Arctic Archipelago and Beaufort Sea

The tides in the Arctic Archipelago vary from semi-diurnal to diurnal, semi-diurnal being more predominant.

The waterways of the eastern Arctic are affected by Atlantic tides with ranges of 2 to 3 m on the average and large ranges, over 6 m. In the western and central Arctic and around most of the Queen Elizabeth Islands, Arctic tides predominate and normal ranges are generally less than 1 m. As a result, tidal currents are strong in waterways such as Hell Gate, Penny Strait, and to a lesser degree in Nares Strait and Byam Channel. The sea-ice regime in all these waterways is affected by these currents.

Local anomalies, like funnelling effects of narrow bays, may increase or decrease the ranges between low and high tides. Also, sea-ice cover over large areas will alter tidal levels while complete ice cover or fast ice will retard the time of this tide and decrease the tide amplitudes.

The physiography of certain areas produce strong tidal current, e.g. in Bellot Strait maximum velocities of up to 3.88 m/s have been noted.

Hudson Strait, Hudson Bay and Foxe Basin

In this entire area the tide is semi-diurnal, except for the short stretch between Povungnituk and Port Harrison, on the northeastern coast of Hudson Bay, and Hall Beach, Foxe Basin, where the semi-diurnal rhythm is affected by large diurnal variations.

Hudson Strait serves as a communication between the open ocean and a large "inland" sea; also, it is much narrower at its waist than at either end. These factors affect the range of the tide in Hudson Strait, which, along the northern coast, increases from 5.5 m to about 9 m at Ashe Inlet, decreasing again to 5 m towards Schooner Harbor. In Ungava Bay the tide coming in from the Atlantic increases rapidly toward the end of the bay, reaching a mean range of 12 m at Leaf Basin.

The tide setting into Hudson Bay describes a roughly circular movements, following the contour of the shoreline, starting from the northwestern end of the Bay, moving south along the western shore, and almost petering out along the eastern shore. In the entrance to the bay, the average range of the tide is 1.8 m increasing to 3.6 m along the western shore, after which it decreases gradually along the southern and eastern shores to about 0.30 m at Port Harrison. The tidal rise and fall may sometimes be obscured, particularly near the head of James Bay, by weather effects which may cause the sea level to rise or fall by a metre or more.

Davis Strait, Baffin Bay, and Lancaster Sound

The tidal range increases northward into Davis Strait, but in Baffin Bay high water at the southern entrance coincides with low water at the northern end. In Smith Sound, the tidal range is about 3 m, and in Lancaster Sound, at Resolute, the mean range is 1.2 m. The inlets leading off Lancaster Sound have a mean range under 1.8 m.

East Coast of Newfoundland and Labrador

Along the east coast of the Island of Newfoundland, and along the Labrador coast as far as Cartwright, the tide is mixed but mainly semi-diurnal. Farther north it tends to become more and a more semi-diurnal, being entirely so at Cape Chidley. High water occurs simultaneously along the two coasts, and the tidal range is about 1 m. However, towards the northern end of Labrador (Davis Strait) the range increases considerably.

2.3.4 Waves

2.3.4.1 Wave Climate

Wind-generated wave motion in arctic waterways has received comparatively little attention until fairly recently. Most techniques that have been used to study this problem have been developed for warmer latitudes and the nature of waves in cold regions where air and water temperatures are substantially different may give rise to inaccuracies by using such methods.

Wave Conditions Arctic Archipelago

In the Arctic Archipelago waterways, in the July to October period, fetches may be restricted by the presence of sea ice as well as the size of the water bodies themselves. Additionally, the presence of scattered ice floes within a fetch will give rise to varying attenuation of wave amplitudes so that it is generally not meaningful to attempt a forecast of waves in such conditions. The Sverdrup-Munk-Bretschneider (SMB) technique (USCERC 1973) was, however, utilized to determine design waves for the Beaufort Sea (Berry et al. 1975).

In later cases, actual ship wind data were used to generate extreme wave distributions by the methods of Thom (1973).

The limited number and uneven distribution of weather observations from ships in the arctic waterways are also the sources of information on wave heights on the sea. Two points should be noted here. Firstly, wave height usually refers to the combination of sea waves (produced by local winds) and swell waves (produced by a distant storm and having travelled to the location in question) but in practice in the restricted arctic waterways, wave height is mainly applicable to sea waves (except possibly along the Baffin Island coast). Secondly, it has been stated that wave heights obtained by visual observations are equivalent to those defined as significant wave heights; that is, the main height of the highest third of all waves in the wave train (Wiegel 1964).

The percentage frequency (or probability) of wave height being greater than specified values are represented graphically in the USNOO Ocean Atlas of the Polar Seas (1958), and the AES climate of Canadian Arctic Islands and adjacent waters, Vol. II (1980) for a 20 years return period.

Wave Conditions Baffin Bay

Wave measurements in Baffin Bay are limited to spring and summer observations. In spring and summer, the sea is generally smooth with wave heights greater than 1.5 m only 10% of the time. In autumn, wave heights greater than 1.5 m have been mapped with 20% frequency in the southeastern part of the Bay according to the U.S. Navy Hydrographic Office (1958).

Wave Conditions Davis Strait

Based on existing observations, it appears that wave climate is most severe in autumn and winter and quite "smooth" in summer. In winter, the seas are dominated by waves from the northwest and an observed wave height greater than 1.5 m in 10% of the observations in the northeastern part of the strait and 50% of the observations in the southwestern part of Davis Strait. In spring, wave heights greater than 1.5 m have a 10% frequency in the northeastern part of Davis Strait and a 30% frequency in the southeastern part. Wave climate in summer is relatively smooth; wave heights greater than 1.5 m occur in 20% of the observations in the southern part of Davis Strait and in 10% of those in the rest of the Strait. The most severe wave climate occurs in autumn, with wave heights greater than 1.5 m in 50% of the observations in the southern part of the strait.

Wave Conditions Labrador Sea and Grand Banks

From September to April, more than 60% of sea waves have significant wave heights which exceeded 2 m, and more than 15% of significant wave heights exceeded 4 m. The more severe storms are in November and December when more than 35% of significant wave heights exceeded 4 m. This compares with less than 5% of significant wave heights exceeding 4 m in the summer months.

For extreme wave conditions in Labrador Sea, the largest significant wave height for normal year and for a 10-year period was calculated as 9.3 m and 12.5 m, respectively (Neu 1982). This compares with significant wave heights of 9.0 m and 12.3 m of similar return periods for Hibernia.

Ice coverage is known to interfere with the propagation of waves. Long waves (swells) tend to be transmitted underneath the ice until friction and turbulence absorbs their energy, while shorter waves will be reflected from the ice edge. The reflected waves will reinforce incoming waves such that heights near the ice edge will be increased (Neu 1982).

2.3.5 Wave Forces

General Description

The study of wave forces on marine and coastal structures can be classified in two ways:

- by the type of structure on which the forces act, and
- by the type of wave action against the structure.

To calculate the wave forces on marine structures, there are two distinct approaches: a deterministic approach, which itself may be either pseudo-static or time dependent (i.e. dynamic), and a stochastic approach. In the deterministic pseudo-static method, which is simplest to use, maximum loads are calculated and applied to static analysis of the structure, whereas in the time-dependent method, a time record of the free surface elevation is used to calculate time-dependent loads, taking into account the dynamic response of the structure. In the stochastic approach, which complements the deterministic approach, the wave motion is treated as a random process and is described by its spectral density (Sarpkaya and Isaacson 1981).

For engineering purposes, it is customary to analyze the effects of surface waves on structures either by use of a single design wave chosen to represent extreme storm conditions in the area of interest, or by use of a statistical representation of waves during extreme storm conditions. In either case, it is necessary to relate the surface-wave data to the water velocity, acceleration, and pressure beneath the waves. This is achieved by the use of an appropriate wave theory. Wiegle (1964), U.S. Army (1973). Sarpkaya and Isaacson (1981) and Dawson (1983) have described in details different wave theories (e.g. linear wave theory or Airy theory, Stokes non-linear wave theory and Cnoidal theory for long, finite-amplitude waves, solitary wave theory, and stream function wave theory of Laplace equation and the forces arising from each theory on different types of offshore and coastal structures. In this chapter, however, only some simple relationships which are deemed to be useful to the designer for estimating some of the wave properties and forces on structures are presented.

Relation of wave height parameter to significant wave height H_s (based on cumulative Rayliegh probability distribution)

Average height = $0.64\ H_s$
Average of highest 10% = $1.29\ H_s$
Average of highest 1% = $1.68\ H_s$
Highest wave height = $1.87\ H_s$

Wave Celerity, length and period

The general expression for wave celerity (or phase velocity) C, derived from Airy's small amplitude wave theory is given by:

$$C^2 = \frac{gL}{2\pi} \tanh \frac{2\pi d}{L} = \left(\frac{L}{T}\right)^2 \qquad (2.3.5)$$

where g is gravitational acceleration, L is wave length, d is water depth and T is wave period. In deep water ($d > L/2$) the above equation is reduced to

$$C = \sqrt{gL/2\pi}$$

The values $2\pi/L$ and $2\pi/T$ are called wave number K and wave angular frequency ω, respectively. From equation (2.3.5) an expression for wave length as a function of depth and wave period is then obtained:

$$L = \frac{gT^2}{2\pi} \tanh \left(\frac{2\pi d}{L}\right) \qquad (2.3.7)$$

For shallow water ($d/L < 1/25$) equation (2.35) is reduced to

$$C = \sqrt{gd}$$

The Sinusoidal Wave Profile

The equation describing the free surface as a function of time t, and horizontal distance x for a simple sinusoidal wave can be shown to be:

$$\eta = \frac{H}{2} \cos \left(\frac{2\pi x}{L} - \frac{2\pi t}{T}\right) \qquad (2.3.9)$$

where η is the elevation of water surface relative to still water level (SWL) and H is wave height.

Local fluid velocities and accelerations

In wave force studies, it is often desirable to know the local fluid velocities and accelerations for various values of z, x, and t during the passage of a wave, where z is the vertical distance measured from SWL (positive upward). The horizontal component u and vertical component w are given by:

$$u = \frac{H}{2} \frac{gT}{L} \frac{\cosh [2\pi (z + d)/L]}{\cosh (2\pi d/L)} \cos \left(\frac{2\pi x}{L} - \frac{2\pi t}{T}\right) \qquad (2.3.10)$$

$$w = \frac{H}{2} \frac{gT}{L} \frac{\sinh [2\pi (z + d)/L]}{\cosh (2\pi d/L)} \sin \left(\frac{2\pi x}{L} - \frac{2\pi t}{T}\right) \qquad (2.3.11)$$

The local fluid particle accelerations are obtained by differentiating above equation with respect to time:

$$a_x = \frac{du}{dt} = \frac{g\pi H}{L} \frac{\cosh [2\pi (z + d)/L]}{\cosh (2\pi d/L)} \sin \left(\frac{2\pi x}{L} - \frac{2\pi t}{T}\right) \qquad (2.3.12)$$

$$a_z = \frac{dw}{dt} - \frac{g\pi H}{L} \frac{\sinh [2\pi (z + d)/L]}{\cosh (2\pi d/L)} \cos \left(\frac{2\pi x}{L} - \frac{2\pi t}{T}\right) \qquad (2.3.13)$$

As mentioned previously, the precise evaluation of the forces exerted upon an object by ocean waves is extremely complicated because of the many interacting phenomena that are involved. Among the most important of these factors are: the non-linearity of the water particle displacement and kinematics, the variability of the wave profiles and forces, turbulence, and possibility of dynamic effects such as vortex shedding and structure resonance. Wave force equations also represent an unsteady, non-uniform flow condition for which dynamic effects are non-deterministic. The calculation of wave forces involves the selection of the appropriate wave theory to describe the particle kinematics and displacements for a given design conditions, and also, a choice of a semi-empirical coefficients (e.g. drag coefficient, inertia coefficient, etc). The attempt herein is to describe the general equation of wave forces on a structure. The reader should refer to the references cited, for more details.

The force per unit length exerted on a fixed vertical cylinder (for simplification) is described in Morison equation (described in Section 2.3.2) now widely used in engineering calculations:

$$F = \frac{1}{2} \rho C_D D|u|u + \rho C_M (\frac{\pi D^2}{4}) a_x \qquad (2.3.14)$$

The drag and inertia coefficients (C_D and C_M) were described previously in Section 2.3.2. The values of velocity u and acceleration a_x in equation (2.3.14) are calculated from an appropriate wave theory (e.g. equations 2.3.10 and 2.3.12) and, together with chosen values of the drag and inertia coefficients, the equation yields, at any instant in the wave cycle, the force distribution along the cylinder.

At shallow water sites, and especially where strong steady state currents are present, transverse "lift" forces may occur as a result of vortex shedding. At certain flow speeds, as dictated by Reynolds number (R_e), a periodic shedding of turbulent vortices from alternate sides of the pile may occur, giving rise to transverse lift force (equation 2.3.3). The frequency of vortex shedding is given by the Strouhl number $N_s = Df/v$, where D is diameter of structure, f is frequency and v is the flow velocity. The value of N_s varies with shape of the structure and R_e (see Gaythwaite 1981), e.g. for a cylinder $N_s = 0.2$. Various eddy-shedding regimes can be defined dependent on the Keulegan-Carpenter number K_c (see the U.S. Army Shore Protection Manual for values of C_D, C_M and C_L).

Waves in Shoaling Water

Wave refraction, diffraction, reflection and breaking are all important in the design of coastal structures. Wave-induced sediment transports along coast line (littoral transport) or near structures foundations should be studied in detail in order to ensure the integrity of coastal structures (U.S. Army Shore Protection Manual 1973).

Scouring and Deposition

Wave action may cause scouring of loose bottom material, especially fine sands and silts, thus affecting the stability of a structure's foundation. Water waves induce an orbital motion in the fluid beneath them. These are not closed orbits, and the fluid experiences a slight wave-induced drift, or mass transport. The magnitude and direction of mass transport are functions of elevation above bottom and wave parameters, and are also influenced by wind, temperature gradient and other ocean currents (see Section 2.3.2). The action of mass transport, extended over a long period, can be important in carrying sediment onshore or offshore.

As waves approach breaking, wave-induced bottom motion in the water becomes more intense, and its effect on sediment becomes more pronounced. Breaking waves create intense local currents (turbulence) that move sediments.

Scouring is an important consideration in structural design, as the removal of sand may cause undermining of mat foundations and increase the effective column length of pile type structures. In general, mat foundations should be designed with adequate scour protection or with the assumption that 20% to 50% of the bottom support will be removed by scouring. Likewise, the design of pile structures should consider the effects of increased unsupported length of piles. For more details, refer to U.S. Shore Protection Manual (1973); U.S. Navy Design Manual-Harbour and Coastal Facilities (1968); Wiegel (1964); Sarpkaya and Isaacson (1981).

Storm Surges

Storm surges or wind set-up are created by strong winds. The height of storm surge depends on wind velocity and direction, fetch, water depth and near shore slope. Severe storms may produce surges in excess of 7 m on open coast and even higher in bays and estuaries due to funnelling effect in converging estuaries or bays and also may cause resonance in harbours.

Wind-induced surge, accompanied by wave action, accounts for most of damage to coastal engineering works. Moreover, surge can increase hazards to navigation, impede vessel traffic, and hamper harbour operations. A knowledge of the increase or decrease in water levels that can be expected during the life time of coastal structure is necessary for the design of these structures. Thus, the total design water level D.W.L. can be determined as a vector sum of all components that cause rise in water level, i.e. high water of spring tide (HWOST), storm surge or wind set-up wave and pressure or barometric set-up.

The return periods (or frequency of occurrence) of storm surges along a given coast are directly related to the return periods of severe storms. An estimate of the frequency of occurrence of a "design storm" is required. The most common method of making this estimate is to use frequency curves developed from statistical analysis of historical water level data. DeYoung and Fafflin (1975) found that the probability of occurrence (P) of extreme high water nearly follows a log-normal distribution, and that the return period (R_t) is given by the relation:

$$R_t = \frac{1}{12\ (1 - P_1)\ (1 - P_2)}$$

where

$(1 - P_1)$ = probability of exceedance of the astronomical tide, and

$(1 - P_2)$ = probability that wind set-up will be exceeded.

The above equation assumes that any excess water level above the astronomical tide height does not occur until the normal tide has risen to its full height.

In general, not enough storm surges observations are available in many places, particularly in the arctic regions, to make accurate predictions of storm surges. Therefore, the general practice is to use hypothetical design storms, and to estimate the storm-induced surges by physical or mathematical or numerical models. Mathematical or numerical models are usually used, since it is difficult to represent some of the storm surge generation processes (such as direct wind effects and Coriolis effects) in physical laboratory models.

The hydrodynamic equations that describe the storm surge generation processes are the continuity equation (or conservation of mass) and the equations of motion expressing Newton's second law. Derivations and the integration (solution) of these equations are presented in the U.S. Army Shore Protection Manual, Vol. I; Bretschneider (1967), Bodine (1971); Welander (1961), Platzman (1965), Ippen (1966).

Recently, many numerical models have been developed to solve the storm surges equation using different numerical techniques. For details reference should be made to: Roache (1972), Heaps (1969), Leendertse (1970), Abbott et al. (1973).

CHAPTER 3

ICE TECHNOLOGY

3. ICE TECHNOLOGY

3.1 Morphological Properties of Ice

3.1.1 Atomic Structure of Ice

The most elementary crystallographic structure of ordinary ice, ice I (Weeks and Ackley 1982 - Vol. 2, Page 57), consists of a regular tetrahedron formed by four oxygen atoms symmetrically distributed around a central oxygen atom. The entire network of these structures are held together by hydrogen bonds with two hydrogen atoms near each oxygen atom. The tetrahedral order of the oxygen atom produces an open, low density crystal structure with hexagonal symmetry.

Bases of the elementary tetrahedrons are concentrated on planar hexagonal surfaces which are referred to as basal planes (Figure 3.1).

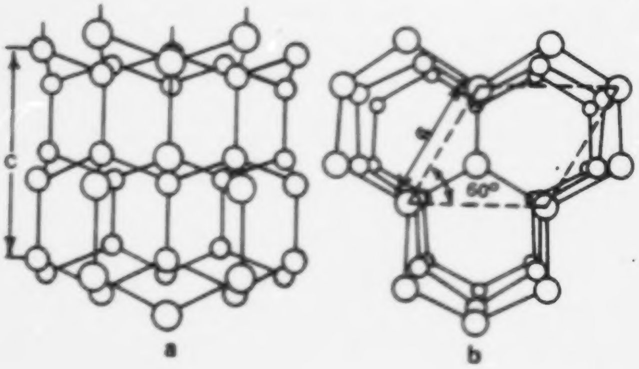


Figure 3.1 Continuous molecular structure of ice. The lines joining the oxygen atoms represent bounds. The hydrogen atoms are not shown.

a) View perpendicular to the c-axis whose length is shown.

b) View along the c-axis where the distance a in the basal plane is shown.

The direction perpendicular to the basal plane is the principal hexagonal axis, or c-axis. The crystalline system is such that fracture of the crystal along the basal plane involves the rupture of half as many bonds as fracture along any plane parallel to the c-axis. Consequently, an ice monocrystal exhibits strongly anisotropic deformation and strength properties and a preferential direction of growth perpendicular to the c-axis.

Impurity atoms that are of a similar size and charge and form a similar chemical bond to atoms comprising the structure of ice crystals are not present in significant amounts in natural water bodies. Consequently, ice crystals formed by freezing, even in concentrated solutions, can be considered pure.

3.1.2 Definition of Ice Types

Ice formation may develop under either static or dynamic condition, both of which dramatically affect the formation and characteristics of the primary ice layer or P ice and indirectly affect the secondary or S ice layer (Michel and Ramseier 1971 - Vol. 2, Appendix 2). For example, in calm water the primary ice is a thin layer which grows horizontally in the supercooled water layer. Secondary ice will grow perpendicular to and beneath this ice skim parallel to the direction of heat flow. Conversely, in turbulent waters the primary ice may consist of thick layers of frozen frazil slush nucleated by congealed snow slush should a snowfall occur. The secondary ice layer may also consist of frazil or snow slush deposited under a primary ice layer.

Once an ice cover has formed flooding of the primary layer from any water source will produce a layer of superimposed ice. If snow is on the primary ice surface then snow ice will be formed.

In order to determine the various properties of ice that are significant to the solution of ice-structure interaction problems, it is necessary to have an understanding of the characteristics of different ice types found in nature. Michel (1975 - Vol. 2, Appendix 2) has developed a classification system which defines ice types found in river, lake and in some sea ice conditions (Table 3.1). The classification is based upon the crystal size, shape and crystallographic orientation of the ice layer.

3.1.3 Structural Development of Various Types of Ice

3.1.3.1 Pure Ice

Pure water under absolute calm conditions with no foreign substances present to act as growth nuclei can be supercooled to temperatures as low as -40°C before homogeneous nucleation occurs (Glen 1974 - Vol. 2, Appendix 2). Once the nuclei are present, ice crystal growth is controlled by the rate of heat dissipation through the water column.

Ice crystals initially develop from spherical nuclei to discoid to hexagonal dendritic growth shapes by spreading most rapidly over the water surface in directions parallel to the crystallographic a-axes orientation. The crystals continue to grow until a thin layer is formed over the entire water surface.

Ice Zone	Class.	Environmental Condition	Grain Size (mm)	Grain Shape	Orientation C-axis
Primary Ice	P1	Calm surface, small temperature gradient	5-20	Irregular	Vertical
	P2	Calm surface, large temperature gradient	1->20	Tabular to needle-like	Random to vertically preferred
	P3	Agitated surface nucleated from frazil	<1-5	Tabular	Random
	P4	Nucleated by snow	<1-5	Equiaxed	Random
Secondary Ice	S1	Calm conditions	5->20	Columnar, irregular	Preferred vertical C-axis orientation
	S2	Calm conditions	<1->20	Columnar, irregular	Preferred horizontal C-axis
	S3	Calm conditions	1-20	Columnar, irregular	Preferred aligned horizontal C-axis
	S4	Agitated under ice condition, congealed frazil slush	<1-5	Tabular	Random
	S5	Drained congealed frazil slush	<1-5	Angular	Random
Superimposed	T1	Snow ice	<1-5	Round to angular (equiaxed)	Random
	T2	Drained snow ice	<1-5	Round	Random
	T3	Superimposed - layers of columnar ice formed on layered ice, top of primary ice			
Agglomerate	R	An agglomeration of ice pieces of various types and forms which have refrozen such as rafted or ridged ice			

Table 3.1 Ice Cover Classifications (fr. Michel 1975)

As secondary ice grows into the water column, the strongly preferred orientation of the initial primary ice skim with c-axes vertical gives way to one in which the c-axes becomes horizontally aligned. Perey and Pounder (1958 - Vol. 2, Appendix 2), found that almost all of the crystals formed from distilled water frozen under still conditions exhibited horizontal c-axis alignment at the depth of 20 cm. They discovered that preferred growth along the basal planes leads to the wedging out of crystals with a preferred vertical c-axis orientation (Figure 3.2). As a result, crystals develop an elongation in vertical dimensions with depth forming a secondary ice type characterized by columnar grains with the length of crystal growth being determined by the temperature gradient in the ice sheet.

3.1.3.2 Fresh Water Ice

In natural situations the structural development of fresh water ice is very similar to that of pure ice however the presence of dissolved or suspended impurities and the interaction of various environmental parameters with the water column result in the heterogeneous formation of ice crystals under static and dynamic conditions at much warmer temperatures than pure water.

Fresh water ice displays a similar crystal platelet structure to pure water ice. However, as water conditions are rarely completely calm initial crystal growth usually exhibits a random c-axis orientation with crystal shape being controlled by the degree of water turbulence during the freezing process. The freezing of fresh water is commonly characterized with the growth of needle shaped crystals inclined at various angles to the water surface. These crystals, with continued supercooling of the water column develop more complex pyramid shaped crystal structures (Weeks and Ackley 1982 - Vol. 2, Page 57) which undergo geometric selection and preferred horizontal c-axis orientation with depth.

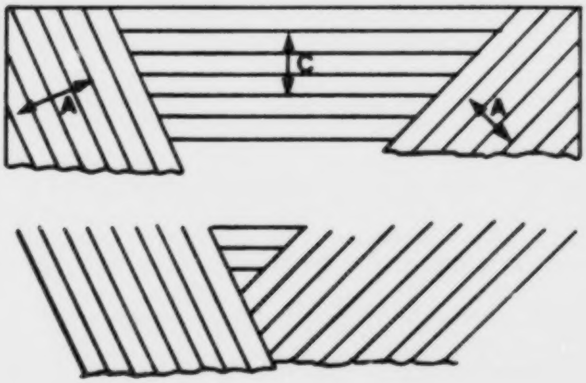


Figure 3.2 Preferred growth of crystals with inclined c-axes, resulting in gradual extinction of a vertically oriented c-axis crystal. The arrows indicate the direction of the c-axes. Crystal A will eventually eliminate crystal C.

The concentration of impurities in fresh water is typically measured at a few hundred parts per million and is not considered a factor in relation to the thermal constants of water and ice, but does have an effect on the ultimate strength of fresh water ice in relation to the direction of tests with respect to the preferred crystal axis orientation. The impurities that are present in fresh water ice are primarily concentrated along grain boundaries and represent weak zones in the ice. This structural characteristic produces a decay process commonly referred to as "candling" during which ice initially decays along the grain boundaries between columnar crystals.

3.1.3.3 Sea Ice

The growth process and crystallographic structure of salt water ice is similar to that of fresh and pure water ice under calm conditions, however, the turbulent conditions of the open ocean environment and the convective mixing caused by the temperature difference between the freezing point of sea water and the temperature of maximum density (see Figure 3.3) often creates an instability during the initial freezing process characterized by agglomerations of frazil ice crystals that exhibit many forms such as grease and pancake ice (Weeks and Ackley 1982 - Vol. 2, Page 57).

The major difference between sea ice and other ice forms relates to the high concentration of salts (between 32 and 35 o/oo present in sea water resulting in a freezing temperature of -1.8°C. Sea ice crystal substructure is quite different from that of fresh water ice as a result of the characteristic defect structure of each sea ice crystal associated with the entrapment of brine between the ice plates at the non-planar interface. The entrapment of brine between the platelets of pure ice composing individual crystals of sea ice is a result of the expulsion of impurities and the expansion of ice crystals during the freezing process. As freezing continues, platelets thicken and ice bridges develop between them; brine becomes trapped in cells between the platelets and become long vertical cylinders (see Figure 3.4).

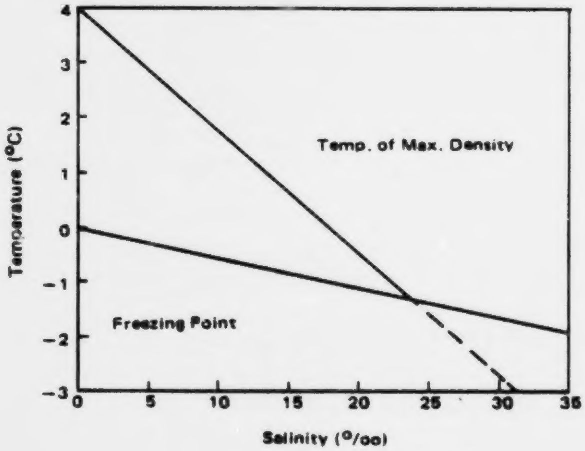


Figure 3.3 The Variation of Freezing Point and Inversion Temperature with Salinity

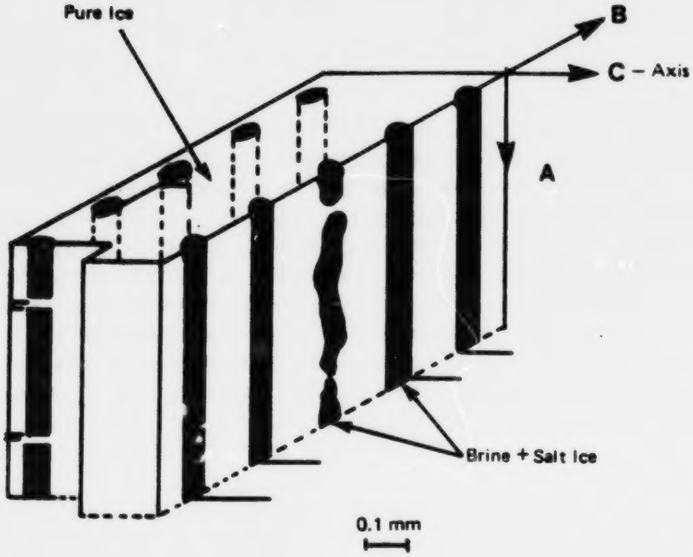


Figure 3.4 Idealized Diagram of the Shape of Brine Inclusions in Sea Ice

The amount of salt entrapped is not constant, but varies systematically with water salinity and ice growth velocity. Very slow growth results in near total rejection of salt from the ice, while very rapid freezing causes near total entrapment. With time the brine will slowly drain through the ice under the influence of gravity and along the characteristic temperature gradient in the ice (see Figure 3.5).

The effect of both factors are additive and result in a marked reduction in brine content over a winter period especially when ice temperatures approach the melting point.

Most first-year sea ice is characterized by salinities in the range of 4 to 12 o/oo. Nakawo and Sinha (1981) found that the salinity of freshly frozen sea ice decreases rapidly during the first week after freezing and then remained relatively constant with a tendency to decrease slowly during the rest of the winter season when temperatures remained below -10 C. They found in their tests that highest salinities were measured at the top and the bottom of the first-year ice layer.

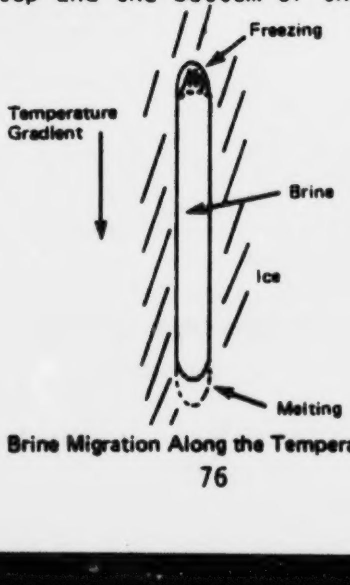


Figure 3.5 Brine Migration Along the Temperature Gradient

3.1.4 Characteristics of Ice Found in Sea Water

3.1.4.1 Multi-Year Ice

First-year ice that has survived one or more summer melt periods is defined as multi-year ice. The characteristic crystal structure and salinity content of first year ice is dramatically deformed and altered during the summer melt due to percolation and ponding of relatively fresh surface melt water. This process results in an ice sheet with very low salinities (<1 o/oo) above water level and salinities of between 2 and 3.5 o/oo below water level. Once the brine has drained from the upper portion, the ice is quite porous and it may recrystallize. Ice that has survived several summers ultimately becomes a layer-cake of the annual layers formed during successive water periods of growth. Successive summer melts in the ice sheet located above water level can produce an ice layer very similar in crystallographic structure and impurity content to that of first-year ice. Undeformed multi-year ice in the Arctic Basin is believed to reach an average steady-state thickness of 3 to 5 m (Weeks and Mellor 1983 - Vol. 2, Appendix 2) at which time the thickness ablated during the summer equals the thickness grown during the winter.

3.1.4.2 Pressure Ridges and Rubble and Hummock Fields

Deformed sea ice thicker than 5 m is commonly found in Arctic regions in the form of pressure ridges and rubble fields produced from the deformation of thinner ice. Pressure ridges formed by compressional or shear deformation from the interaction of first-year ice floes are characterized by randomly oriented, angular ice block and snow filled voids which are poorly consolidated and exhibit complex cross-sections including slush and ice voids.

First-year ridges can become very large. The highest free floating ridge observed had a sail up to 13 m high and a keel which extended to 50 m deep. Ridges of this size are rare as most sails are less than 6 m in height (Wright et al. 1978 - Vol. 2, Appendix 2).

Multi-year ridges, which have survived one or more summer melt periods, consist of a solid mass of ice without cavities or interblock voids characteristic of first-year pressure ridges. The melt water produced during the summer months drains into the core of the ridge and refreezes cementing ice blocks together into a solid, resistant mass of ice. Angular ice blocks gradually become rounded through ablation. As a result of flushing and gravitational and temperature gradient, brine drainage salinity contents in multi-year pressure ridges are very low ranging between 0 to 6 o/oo with minimum concentration found at the top of the sail and a gradual increase with depth.

Multi-year pressure ridges with maximum dimensions characterized by 11 m sails, 31 m keels (a consistent 1:3 keel to sail ratio) and 150 m widths have been measured in the Beaufort Sea (Wright et al. 1978 - Vol. 2, Appendix 2).

The association of multi-year pressure ridges with multi-year ice floes results in a very large feature which presents a severe problem in the design of offshore structures due to their massiveness and structural integrity.

Rubble field generation is a result of the movement and failure of thin ice sheets against grounded features such as artificial islands and shallow coastal zones. It can be formed in a matter of a few days depending upon ice thickness and the rate and direction of ice movement. The formation develops from the continuous deformation, flexural failure and rafting of a thin moving ice sheet which produces an unconsolidated pile of randomly oriented ice blocks (see Figure 3.6).

Once the initial pile is formed and a limiting height is determined by uplifting force levels, rubble generation is initiated further seaward. This sequence of accretion and loss continues seaward during the winter period in a series of pile-ups of increasing heights with increasing ice thickness and block dimensions until the first-year ice sheet becomes landfast.

The internal structure of rubble fields are composed of a top consolidated ice layer followed by a randomly mixed distribution of solid angular ice blocks, voids and soft or slushy ice. Grounded rubble fields in the landfast ice region of the Beaufort Sea have been measured with sail heights of as much as 13 m. Salinity profile and concentrations are similar to those found in first-year pressure ridges.

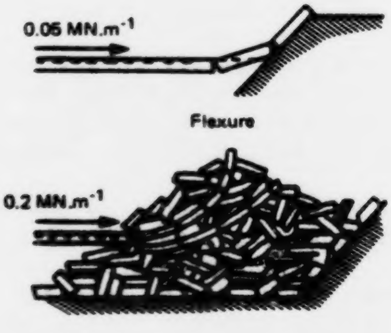


Figure 3.6 Ice Failure Mode in Rubble Field Formation

Multi-year hummock fields are formed by large grounded rubble fields which, with time, ablate at the surface and float away (Hudson 1983 - Vol. 2, Appendix 2).

They have predominantly been found on the west side of the Canadian Archipelago near the northen part of Prince Patrick, Brock, and Border Islands adjacent to the permanent polar pack.

These ice features tend to differ from multi-year floes in their mass and extent and recently have been defined as a multi-year floe which has a diameter of greater than or equal to 500 m and an average thickness greater than or equal to 10 m (Marcellus and Morrison 1982 - Vol. 2, Page 245).

The size of multi-year hummock fields average approximately 1 to 2 km in length by .5 to 1 km wide with average thickness greater than 20 m. Since they are formed from ice rubble, they develop a very irregular and varied geometry comprised of several multi-year ridges with sails and keels averaging 20 m and 60 m respectively. Internal structure and brine content are similar to old multi-year floes and pressure ridges.

3.1.4.3 Icebergs and Ice Islands

Icebergs are formed from the calving off of tidewater landbased glaciers primarily located along the west Greenland coastline. It is estimated that approximately 20,000 to 40,000 are produced from the glaciers along this coastline each year

The calving off process creates icebergs of varying shapes, sizes and drafts. In Baffin Bay berg heights up to 213 m have been measured and heights over 100 m are common in some Greenland fiords. Lengths of bergs can reach up to 1 km with weight estimates reaching as high as 20 million tonnes (Markham 1981- Vol. 2, Appendix 2).

Glaciers are formed by a sedimentation process involving the visco-plastic compaction of dry snow into granular, isotropic ice. Glaciers are covered by an upper snow layer which forms into ice from depth hoar at depths from 40 to 150 m depending upon mean site temperatures. The percolation and refreezing of water in the snow and fiord can also create layers of solid ice in the upper sections of a glacier.

Surface temperatures and crystallographic structure of an iceberg floating in sea water vary seasonally and according to drift patterns whereas internal temperatures remain more constant even during extensive surficial ablation in summer periods.

Icebergs that break off from the main Greenland calving zones generally drift in a northward pattern to Melville Bay and Cape York before heading southward along the Baffin Bay-Labrador shoreline and onto the Grand Banks. The general time frame required for an iceberg to reach the Grand Banks from the calving process is approximately two to three years. During this time period the melting process is occuring on a seasonal basis both below and above the sea surface as a result of warm water temperatures and wave erosion as well as the atmosphere effects of air temperatures, radiation and rainfall.

The internal mechanical properties of icebergs are comparable to that of fresh water ice. As a result of unpredictible drift patterns, and buoyancy as well as massiveness and structural integrity, icebergs represent an intense local hazard to navigation and oil and gas exploration along the Canadian East Coast.

Ice islands that are frequently found in the Beaufort Sea are tabular icebergs which calve from the Ward-Hunt ice shelf on the north coast of Ellesmere Island and become trapped in the polar pack and move about the Arctic Ocean. These ice islands can have highly variable lateral dimensions ranging from more than 10 km to a few tens of metres for ice island fragments. They can be as thick as 70 m and have life spans over 30 years.

Ice islands are composed of a complex mix of ice types which include lake, snow, sea and brackish ice (Weeks and Mellor 1983 - Vol. 2, Appendix 2). As ice islands tend to be tabular in form ponding occurs at the surface during the melt season resulting in ice characterized by medium to coarse grained, long, columnar crystals. Snow ice is also found in the upper layers of ice islands and is formed as a result of the densification and recrystallization of snow. These crystals are typically smaller, randomly oriented and exhibit an equant and euhedral shape and mosaic texture. Salt water ice is generally present in the lower portion of the ice shelf and is characterized by salinities of <2 o/oo. Crystals exhibit the characteristic elongation of columnar zone salt water ice.

Although the presence of large islands are rare, and return periods for collision with a fixed platform are in the order of a thousand years, structures to be used for permanent offshore platforms must nevertheless be designed to withstand these extreme ice feature.

3.2 Mechanical Properties of Salt Water Ice

3.2.1 Parameters of Importance

3.2.1.1 Grain Size and Crystal Orientation

Parameters of grain size and orientation are the characteristics defining homogeneity (or inhomogeneity) and isotropy (or anisotropy) of ice. Most available test results for salt water ice are for specimens of columnar ice which represents best the average properties of ice sheets as far as horizontal strength is concerned since it usually forms the thickest zone. Wang (1979 - Vol. 2, Page 55) presented compressive strength results for granular and columnar salt water ice: generally, finer grained ice offers a higher strength.

The influence of anistropy is very marked for oriented columnar ice. For example, Wang (1979 - Vol. 2, Page 55) reported variations in compressive strength from 9 MPa to 3.5 MPa for directions respectively parallel and at 45 degrees to the c-axis orientation.

Due to the columnar structure of most ice sheets, uniaxial strength properties vary widely if specimens are loaded parallel or perpendicular to the plane of the ice sheet. The grain boundaries and the basal planes of individual crystals, which are the planes where brine pockets are located, represent weak zones in the ice where failure occurs more easily when loaded perpendicular to the growth direction. Typically, the strength of the vertical direction is about three times that in the horizontal direction.

3.2.1.2 Brine Volume

The relationship between brine volume and strength is relatively well explained by a simple model due to Schwarz and Weeks (1977 - Vol. 2, Page 34). The presence of brine pockets reduces the area of contact between platelets and causes failure planes in the ice to follow weak contacts. Strength in a direction perpendicular to the ice columns may be expressed as:

$$f = f_0 (1 - p) \qquad (3.1)$$

where p is the porosity and f_0 is a fictitious strength corresponding to zero porosity. If the voids are assumed to have the shape of vertical cylindrical channels, p is proportional to the square root of the brine volume ν. Equation 3.1 takes the form:

$$f = f_0 \left(1 - \sqrt{\frac{\nu}{\nu_0}}\right) \qquad (3.2)$$

and ν = brine volume where ν_0 is a constant.

This simple model agrees quite well with strength test results. It should be noted that for high values of the brine volume ($\nu > 0.3$ to 0.5), experimental results indicate that there is no further reduction in strength. Under these conditions, large interconnecting drains are formed in the ice allowing the brine to drain out freely. Further discussion is under 3.2.1.5.

3.2.1.3 Strain or Stress Rate

When an ice specimen is loaded, its deformational behavior, failure mechanism and strength are highly influenced by the rate at which strains are being developed. Three ranges of strain rates may be distinguished: ductile, transition and brittle.

At very high rates of loading, other effects are important which are discussed below. Stresses at high speeds are influenced by:

1) strain rate effect;
2) impact velocity;
3) drainage effect.

Ductile Behavior

When subjected to low rates of loading or sustained loads, ice creeps. As strains are slowly increased, a ductile failure is reached: the maximum stress which is attained is referred to as the yield strength. The behavior in this zone is controlled by the number of mobile dislocations occurring along the basal planes in the ice crystals. As evidenced in Figure 3.7, the effect of strain rate on the yield strength of salt water ice is extremely significant.

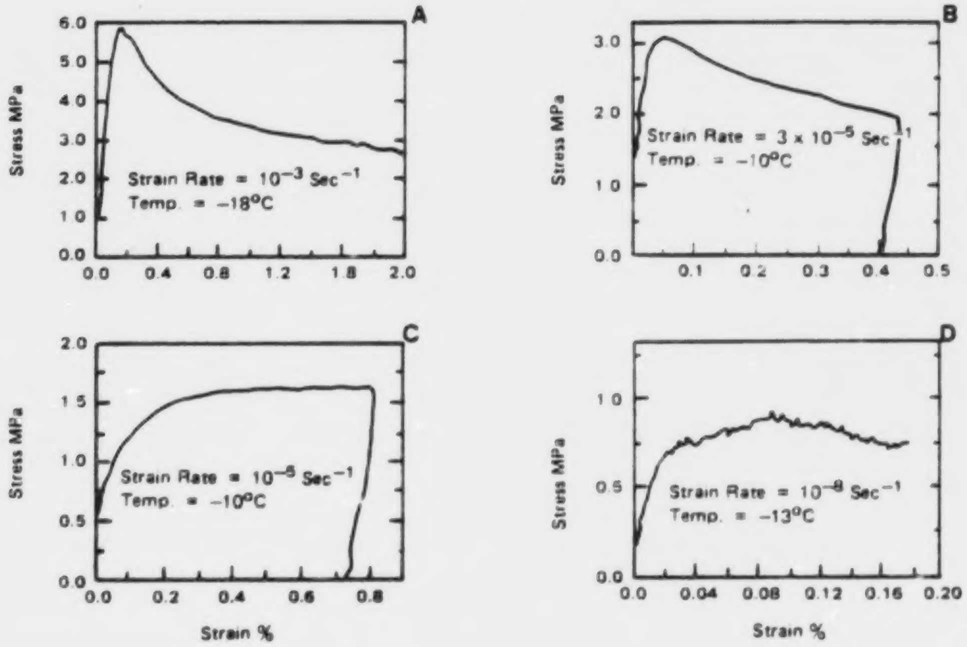


Figure 3.7 Typical Stress-Strain Diagrams for Salt Water Ice Specimens in Uniaxial Compression (Wang, 1981)

For low rates of compression strains in constant strain rate tests, the dependence of the yield stress on the strain is in good agreement with the dependence of secondary creep rate on the stress in a constant load test. A power law is frequently used to describe secondary creep in ice:

$$\dot{e} = f^n A \exp\left(-\frac{Q_c}{R\Theta}\right) \qquad (3.3)$$

which is often associated in glaciology literature, with Glen (1955 - Vol. 2, Appendix 2). In this expression, $\dot{e}$ is the strain rate, f the yield strength, Q_c the activation energy for creep in cal/mole °K, R the universal gas constant equal to 1.986 cal/mole, Θ, the absolute temperature in °K and A a proportionality constant. The constant n which defines the slope on a log-log plot of yield stress as a function of the strain rate is approximately equal to 3.

To eliminate the effect of temperature which will be discussed subsequently, equation 3.3 may be expressed in the form:

$$f = f_0 \left(\frac{\dot{e}}{\dot{e}_0}\right)^{\frac{1}{n}} \qquad (3.4)$$

where the yield stress for a given strain rate $\dot{e}$ is related to some reference strength f_0 and corresponding strain rate $\dot{e}_0$, usually chosen to correspond to the peak value of strength at the upper limit of the ductile range of behavior.

Brittle Behavior

Rapidly applied loads, on the other hand, cause a sudden, brittle failure. At high strain rates, dislocation velocities are too slow to allow ductile behavior so that the mechanisms of fracture initiation and propagation control the strength in this range of strain rates. Analytical models have been found to provide fair correlations with observed strength properties: a Griffith approach was used by assuming the crack of critical size for propagation to be elongated for columnar ice and penny-shaped for granular ice (Gold 1972 - Vol. 2, Appendix 2). In the brittle domain, the behavior before fracture is essentially elastic; strength is determined by the grain size and temperature and is considered to be rate-independent although some indication of an increase in strength due to a different mode of failure for strain rates above 1 s^{-1}, have been given (Coburn et al. 1981 - Vol. 2, Appendix 2). For fresh water ice, Michel (1978 - Vol. 2, Appendix 2) gives:

$$f'_c = 0.094\ (\sqrt{d} + 6\ \theta^{0.78}) \tag{3.5}$$

and

$$f'_t = 0.079 \sqrt{\frac{1 - 0.0009\ \theta}{d}} \tag{3.6}$$

where f'_c and f'_t are the compressive and tensile strengths in the brittle range, d is the diameter of the equivalent spherical ice crystal in millimeters and θ is the absolute value of the temperature in °C. For columnar ice, the equivalent diameter d is related to the average grain size by:

$$d = \frac{3\pi d_g}{8} \tag{3.7}$$

In the above equations, one notices the dominant influence of temperature on the brittle compressive strength while grain size essentially controls the brittle tensile strength.

Transition

At strain rates intermediate between the ductile and brittle zones lies a so-called transition zone where the mode of failure is unstable and either ductile or brittle failures may be encountered. Transition strain rates on the order of 5×10^{-4} to 10^{-2} sec.$^{-1}$ are typical for compressive loading of freshwater S2 ice at a temperature of -10°C. Transition rates are much lower for tensile strength, typically on the order of 10^{-6} to 10^{-5} for various types of fresh water ice. The range of strain rates corresponding to the transition zone is temperature-dependent for both compressive and tensile strengths.

In addition to the prevalent increase, a decrease at high rates in compressive strength with increasing strain rate has been observed by many investigators (Peyton 1968b; Michel 1978; Wu, et al. 1976 - Vol. 2, Appendix 2). Although this has been reported to occur in both types of ice, in the case of salt water ice, conditions are often not as well controlled and the additional effect of salinity usually produces a larger dispersion of strength values at high strain rates. Sinha and Frederking (1979 - Vol. 2, Appendix 2), in an investigation of the effect of test system stiffness on strength, noted that a constant rate of crosshead movement of the testing machine produces an essentially constant stress rate through most of the loading but that actual strain rates, measured with strain gauges, only approach the nominal strain rate at the time of failure. At a given nominal strain rate, defined as the ratio of crosshead velocity to specimen length, higher stress rates are produced by a stiff testing machine compared to a flexible system. A stiffer system thus tends to produce a more brittle failure than a flexible test apparatus.

General Formula for Stresses in High Speed Impact

For cylindrical elements of ice, the following formula may be written in the elastic range:

$$p = \rho c v \left(1 + \frac{ct}{s}\right) = \frac{v}{c} E \left(1 + \frac{x/s}{v/c}\right) \qquad (3.8)$$

where:

p = contact pressure
E = modulus of elasticity
c = stress wave celerity
x = displacement of colliding element
s = characteristic length

If a rod of ice is attached to an ice mass at the back, then the dimensions have the following values:

s = characteristic length (length of rod)

$$p = \frac{v}{c} E \left(1 + \frac{x/s}{v/c}\right) = \left(\frac{v}{c} + \frac{x}{s}\right) E \qquad (3.9)$$

At high speed impact the first time, proportional to $\frac{v}{c}$, is important. For a rapid judgement, impact criteria were developed by Johnson related to damage number concept. Below, a modified form of this concept is used.

Impact Criteria

Elastic Criterion

A damage number is written:

$$K_e = \frac{\rho v c}{\sigma_e} \qquad (3.10)$$

where:

σ_e = elastic limit
ρ = density of the target halfspace material
v = velocity of the projectile
c = speed of sound in target material

This equation can be modified:

$$c = \left(\frac{E}{\rho}\right)^{\frac{1}{2}} \qquad (3.11)$$

$$K_{el} = \frac{\rho v E^{\frac{1}{2}}}{\rho^{\frac{1}{2}} \sigma_c} = \frac{v\,(E\rho)^{\frac{1}{2}}}{\sigma_e} \qquad (3.12)$$

In this expression, contact pressure at the first moment of impact is:

$$P_i = v\,(E\rho)^{\frac{1}{2}} \qquad (3.13)$$

Thus the expression becomes:

$$K_e = \frac{Pi}{\rho_c} \qquad (3.14)$$

The expression could be transformed also in the following way:

$$K_e = \left(\frac{\rho v^2}{\sigma_e\ \varepsilon_e}\right)^{\frac{1}{2}} \qquad (3.15)$$

where:

$$\Sigma_e = \frac{\sigma_e}{E} \qquad (3.16)$$

is the elongation at the elastic limit.

Plastic Criterion

The general damage number uses flow stress as parameter since plastic deformations are predominant in the failure of the contact edge of an ice mass.

$$K_p = \frac{\rho v^2}{\sigma_p} \qquad (3.17)$$

where:

σ_p = flow stress
ρ = density of target halfspace
v = velocity of the projectile

Example on structures penetrating ice (or vice versa). Plastic behaviour starts at:

$Kp = 10^{-3}$

It is assumed that $\sigma_p = 8000 \times 10^3$ Pa
and $\rho = 10^3$ kg/m^3

$$v = 2.8 \text{ m/sec.} \qquad (3.18)$$

Quasistatic range would be limited to $K = 10^{-5}$:

The same values give $v = 0.28$ m/sec. (3.19)

In large masses, the rate of drainage becomes critical at high speed impact, and should be considered in comparing two tests of various sizes.

3.2.1.4 Scale Effects

Recent work has related scale effects to fracture characteristics of sea ice. Important investigations were conducted by Urabe and Yoshitabe (Vol. 2, Appendix 2). Sample analysis have been carried out by Hamza and Muggeridge (Vol. 2, Page 95) on ice forces related to fracture toughness.

Scale effects may be defined as the influence of the size of a model test specimen to the actual behavior at full scale in nature. The importance of scale on the strength of brittle materials is well established. Since brittle fracture is usually initiated by a stress concentration at the tip of a crack, and if it is assumed that these imperfections are Poisson-distributed, a larger volume of material is more likely to offer a flaw at an unfavorable orientation than a smaller volume and therefore is likely to fracture at a lower stress value. Weeks and Assur (1969 - Vol. 2, Appendix 2) proposed a law of the form:

$$\frac{f_s}{f_L} = 1 + \frac{L}{L_o} \qquad (3.20)$$

where f_S and f_L are the measured strengths on the small and large scale specimens respectively, L is the square root of the area of the failure surface and L_0 a constant determined from test results which was found to vary with temperature. Although the functional form suggested was found to describe the data very well, its application to salt water ice has yet to be fully verified. Kry (1975 - Vol. 2, Appendix 2) found equation 3.20 to be applicable to his flexural strength results although he warns against extrapolating beyond the largest value for which test results were obtained (L of about 1 m).

3.2.1.5 Temperature Effects

The influence of temperature on the mechanical properties of salt water ice is usually accounted for through the effect of changing brine volume by an expression of the form of equation 3.2. The brine volume γ may be calculated approximately by use of the following equation developed by Frankenstein and Gardner (1967 - Vol. 2, Appendix 2):

$$\upsilon = S\ (0.532 - \frac{48.185}{\theta}) \qquad (3.21)$$

for $-0.5°C \leq \theta \leq -22.9°C$

where ice temperature θ is in °C and salinity S is in parts per thousand (o/oo).

Michel (1978 - Vol. 2, Appendix 2) reports the temperature dependence of strength in the ductile domain to be governed by Glen's creep law, equation 3.3.

The same relationship applies equally to tensile strength and compressive strength in the ductile domain. When ice behaves as a brittle material, temperature has a negligible effect on tensile strength and grain size is the most significant parameter. Temperature as well as grain size are important parameters in the case of brittle compressive strength.

The strength variations with temperature are illustrated for various salinities of salt water ice in Figure 3.2.2. The ratio r which is the quotient of the strength f at the temperature of interest, to the strength f_{-10} at -10°C is plotted as a function of temperature in degrees C.

Figure 3.8 also indicates the effect that increased brine content has on increasing ice compressive strengths at temperatures colder than -10°C. This may be explained by the fact that salt impurities in the ice begin to precipitate near this temperature. As temperatures drop crystallizing salts strengthen the ice.

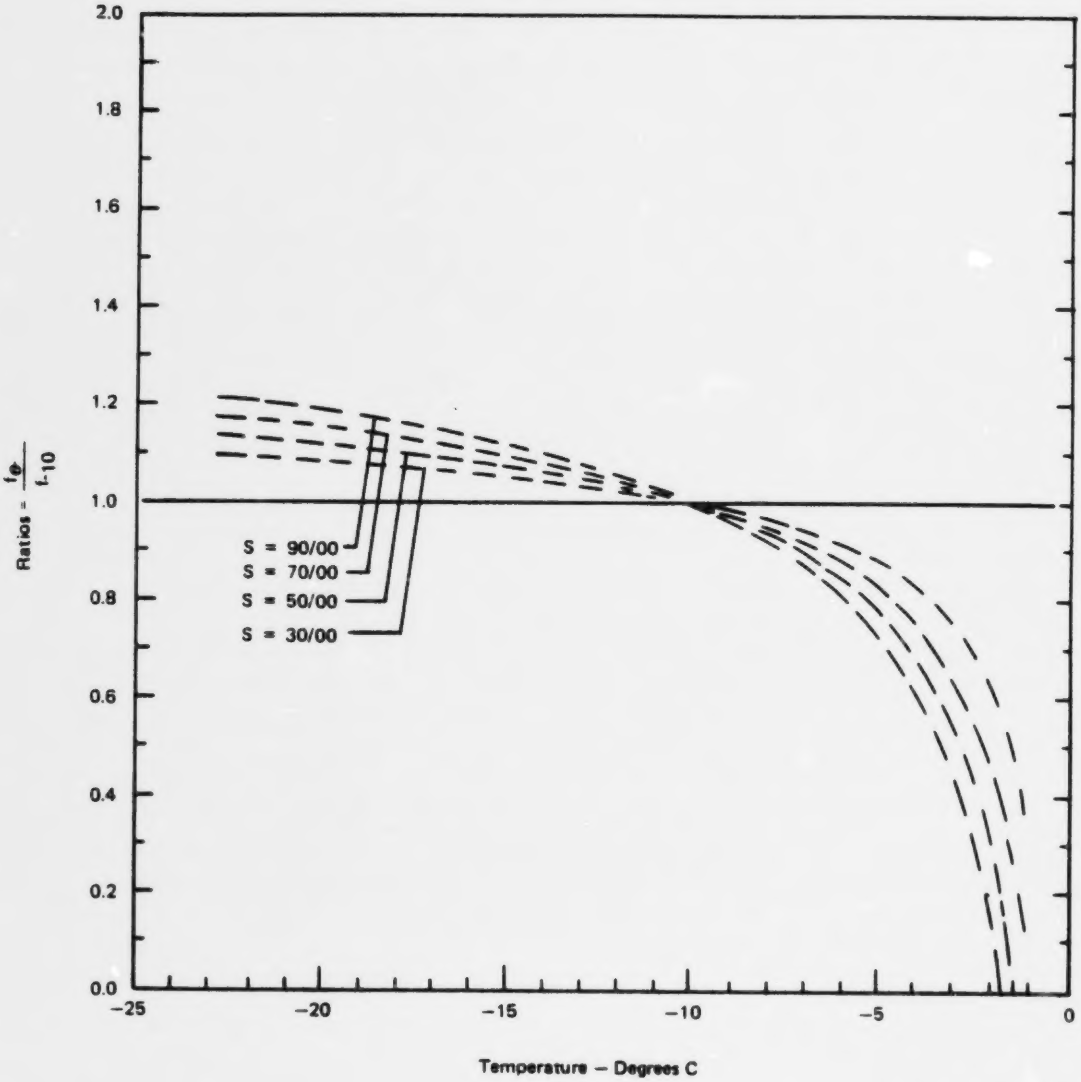


Figure 3.8 Influence of Temperature on Salt Water Ice Strength (From Michel 1978)

3.2.1.6 Confinement

Materials in a confined state being crushed in front of a structure exhibit strength properties which are quite different from that of an unconfined test specimen. Confinement is typically expressed in terms of structure diameter to ice thickness aspect ratio. Analysis of the problem therefore requires an assumed failure criterion for the material which allows a prediction of the forces exerted against the structure. The failure criterion is based on one or several index strength parameters such as the unconfined compressive and tensile strength. Some failure criteria also require multiaxial data for their definition.

Frederking and Timco (1983 - Vol. 2, Page 7), completed confined compression tests on granular and columnar salt water ice at a constant strain rate and temperature. The confinement was tested at the sides (A-type), at the ends (B-type), and unconfined (C-type). For granular ice, confined compressive strength for both A and B-type confinement was 19% higher than for unconfined tests. For columnar ice, the compressive strength for A-type confinement was as much as four times higher than the strength of unconfined or B-type confined compressive strength. The results are due to basal plane glide in the ice and indicate the sensitivity of ice structure to confined tests.

Triaxial compressive strength tests, completed by Nawar et al. (1983 - Vol. 2, Appendix 2) on laboratory grown saline ice, similarly found that ice strength is strongly dependent upon sample orientation. They found that the mean strength ratio of samples parallel to the ice growth direction to samples perpendicular to the ice growth direction was 3.0 at a constant strain rate of $3 \times 10^{-4}\ s^{-1}$.

3.2.2 Strength Properties of Salt Water Ice

Due consideration of the effect of brine volume is required in order to properly establish strength properties of salt water ice. The relationships that follow are presented toward this end. A brief discussion of flexural strength will follow the presentation of the more fundamental compressive and tensile strengths.

3.2.2.1 Compressive Strength

The compressive strength of salt water ice varies with strain rate, temperature and brine porosity. Weeks and Assur (1969 Vol. 2, Appendix 2) analyzed the results of compressive strength tests completed on salt water ice from Cook Inlet, Alaska and suggested a law of the form:

$$f_c = 1.65\ (1 - \surd \frac{\upsilon}{0.275}) \qquad (3.22)$$

where f_c is the compressive strength in MPa and γ the brine volume.

Variations of compressive strengths with brine porosity at high strain rates (approximately 10^{-3} s^{-1}) is shown in Figure 3.9.

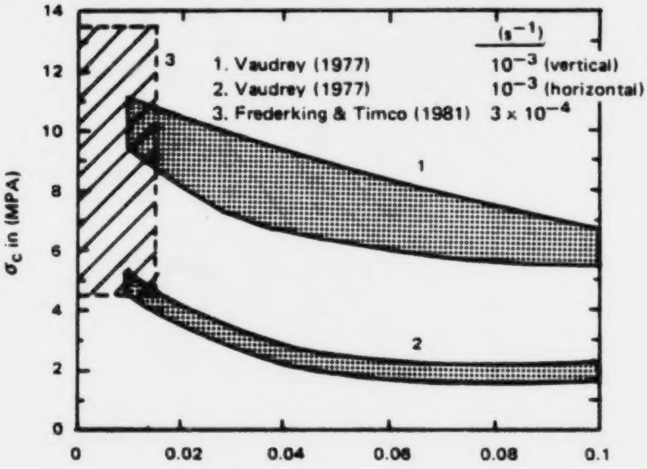


Figure 3.9 Summary of Data of σ_c as a Function of Brine Porosity

Wang (1979 - Vol. 2, Page 55) presented compressive strengths versus strain rate data for granular, unoriented columnar and oriented columnar sea-ice: these are shown in Figures 3.10 and 3.11. As mentioned before, strength values show quite a bit of scatter such that no strength reduction from the transition zone towards the brittle zone is clearly distinguishable except perhaps in the case of granular ice.

It is interesting to note that; 1) the slope in the ductile domain appears to be given by a value of n approximately equal to 3 and 4 for columnar and granular ice respectively, and that; 2) transition strain rates are approximately equal to 5 x 10^{-4} s^{-1} and 10^{-3} s^{-1} for columnar and granular ice respectively.

In Figure 3.12 the effect of temperature on compressive strength is shown for sea ice and for some comparable fresh water ice.

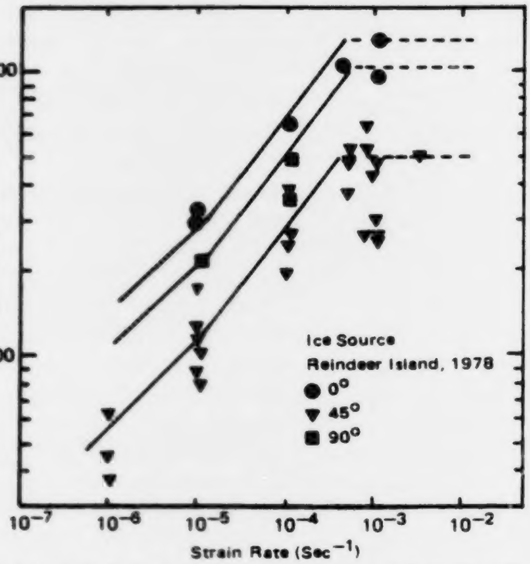


Figure 3.10 Variation of σ_c with Strain Rate in Columnar Sea Ice at -10°C. The Three Data Sets Show the Effect of Crystal Orientation (Wang, 1979)

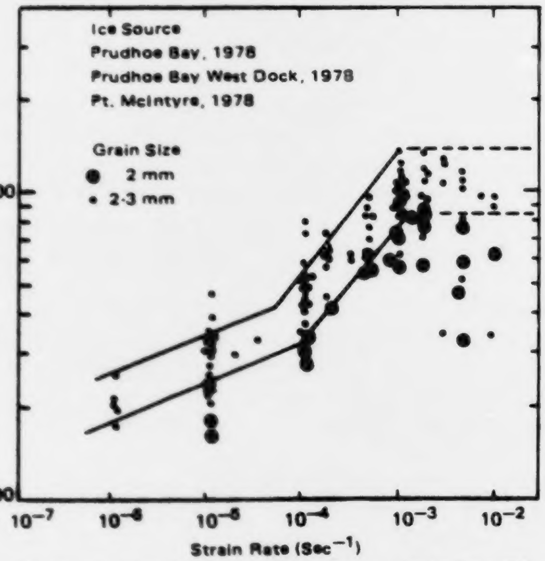


Figure 3.11 Variation of σ_c with Strain Rate in Granular Sea Ice at -10°C. The Effect of Grain Size is also Indicated (Wang, 1979)

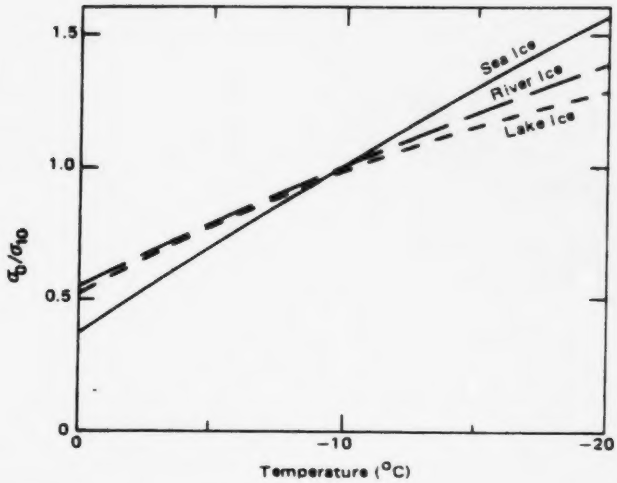


Figure 3.12 Variation of σ_c with Temperature for Three Ice Types (Schwarz, 1971)

3.2.2.2 Tensile Strength

Producing a uniaxial stress field is much more difficult in tension than it is in compression because of the difficulty in maintaining perfect specimen axiality and in avoiding perturbations of the stress field. These difficulties are now being overcome, but new data has not yet appeared. The most useful published data was collected by Dykins (1971 - Vol. 2, Appendix 2) who obtained strength results for both vertical and horizontal directions as a function of the brine content (see Figure 3.13).

Figure 3.13 shows that tensile strength increases with decreasing temperature and salinity and is greater for vertical specimens of columnar ice than for horizontal specimens.

Schwarz and Weeks (1977 - Vol. 2, Page 34) analysed the results of Dykins and proposed the following relations:

$$f_t \text{ (vertical)} = 1.54 \left(1 - \sqrt{\frac{\nu}{0.311}}\right) \qquad (3.23)$$

$$f_t \text{ (horizontal)} = 0.82 \left(1 - \sqrt{\frac{\nu}{0.142}}\right) \qquad (3.24)$$

where the tensile strength values f_t are in MPa.

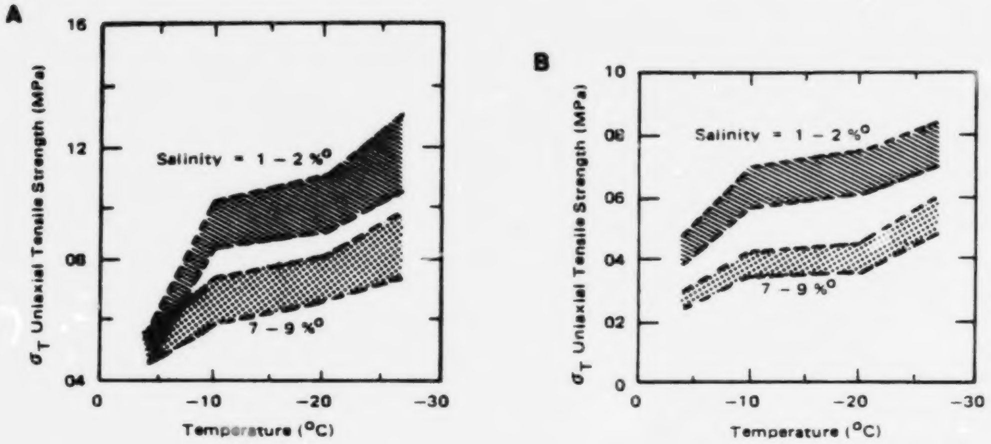


Figure 3.13 Variation of Uniaxial Tensile Strength with Temperature and Salinity for Sea Ice: (A) Vertical Specimens, (B) Horizontal Specimens, Dykins (1970)

3.2.2.3 Flexural Strength

Flexural strength has been measured in many test programs involving both laboratory and field work. The two tests, principally used during such testing programs include simple beam and cantilever beam tests. In situ testing is considered to better preserve natural ice conditions, however, cantilever beam tests have been the subject of much controversy, especially concerning the problem of beam-root stress concentrations, variations in grain structure, steep temperature gradients and scale effects.

Flexural strength may be computed by the standard formula for an isothermal cantilever beam:

$$\sigma_f = \frac{6PL}{bt^2} \qquad (3.25)$$

where P is the failure load, L the span, b the width and t the thickness of the beam. Figure 3.14 presents a summary of results which show the relationship between flexural strength and brine porosity.

Brine porosity, which can be derived from a knowledge of temperature and salinity profiles, can therefore be used to predict flexural strength.

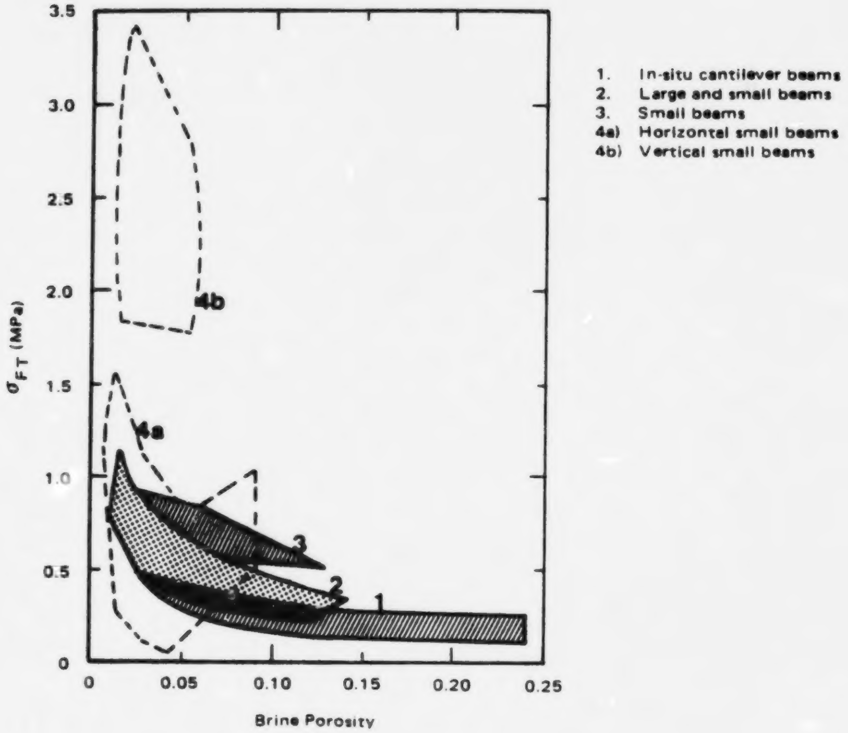
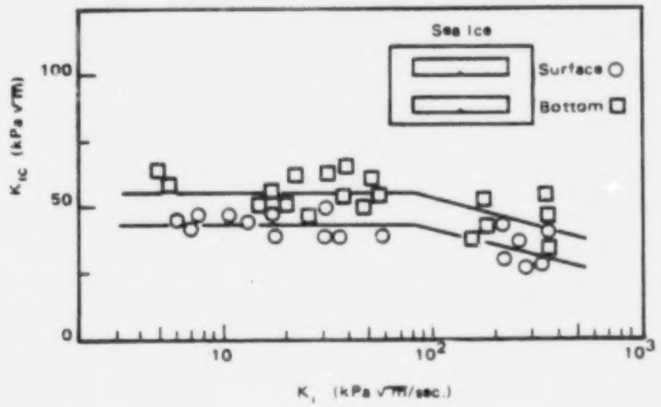


Figure 3.14 Summary of Data for flexural strength σ_{FT} as a Function of Brine Porosity (Weeks and Mellors, – Volume 2, Appendix 2)

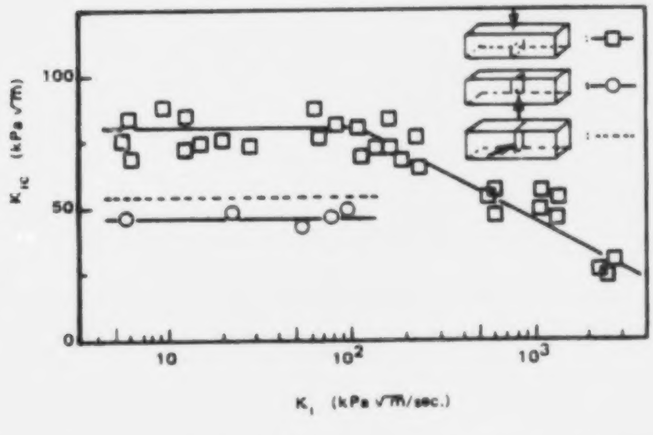
3.2.2.4 Fracture Toughness

Fracture toughness is defined as the critical stress at which a crack in a brittle solid becomes unstable and propagates. It has recently become a subject of interest in the field of ice mechanics in studies of the behaviour of ice at the microscale, however, the technique may become useful at the macroscale for studying the appearance of large cracks propagating ahead of a structure during indentation model tests.

Only opening mode (Mode I) plane strain fracture toughness values K_{IC} have been reported. Urabe and Yoshitabe (1981 - Vol. 2, Appendix 2) have summarized their experimental results as well as those of other investigators for pure and saline ice. Plane strain fracturing tests in fresh water ice have been reported by Hamza and Muggeridge (1979 - Vol. 2, Page 95). Fracture toughness values as a function of the stress intensity rate ($\dot{K}_{IC}$) for salt water ice specimens at -2° are shown in Figure 3.15. As seen from their results, fracture toughness generally decreases with increasing loading rate.



Relationship between K_{ic} and $\dot{K}_I$ for small scale sea ice specimen, cut out from the top portion and from the bottom portion of the ice sheet. (T = −2°C)



Relationship between K_{ic} and $\dot{K}_I$ for large scale sea ice specimen with various loading directions. (T = −2°C)

Figure 3.15 Rate-dependent Plane Strain Fracture Toughness K_{ic} for Sea Ice (Urabe and Yoshitabe, 1981)

Temperature seems to have very little effect on ice at high strain rates, however, at low rates fracture toughness appears to increase as temperatures decrease (see Figure 3.16).

3.2.3 Deformational and Shear Properties

3.2.3.1 Elastic Modulus

At high strain rates, ice behaves as an elastic, brittle material. Describing the deformational properties in this range is therefore quite straight forward and a dynamic modulus E_d (derived by modifying Young's modulus E by an equivalent secant modulus E* obtained by dividing fracture stress by deformation) is applicable for strain rates in excess of 10^{-1} s^{-1} (Michel 1981 - Vol. 2, Appendix 2).

Porosity and brine volume are a major factor in the dynamic modulus of sea ice (see Figure 3.17).

Static measurements of E are much more variable and difficult to interpret than dynamic measurements because of the visco-elastic behaviour of ice when subjected to large loads, at low strain rates, for finite time periods. Murat (1978 - Vol. 2, Page 26) analyzed the test results of Vaudrey and Katona (1975 - Vol. 2, Appendix 2) and proposed the expression:

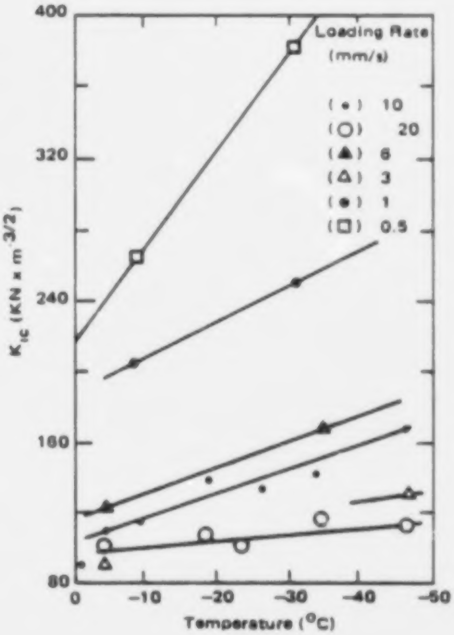


Figure 3.16 Variation of K_{IC} of fresh water ice with Temperature and Loading Rate, Miller, (1979)

$$E = 6920\left(1 - \sqrt{\frac{\gamma}{0.277}}\right) \text{ MPa} \qquad (3.26)$$

giving static values about one third of dynamic measurements.

Sinha (1981 - Vol. 2, Page 37) has shown that the lower effective modulus of sea ice compared to pure ice is primarily due to the differences in microstructure and not necessarily the salt content. He suggested that subgrain or platelet spacing may be the dominant factor producing lower values of the modulus, thus allowing predictions of the modulus to be made on the basis of grain (or subgrain) dimensions alone.

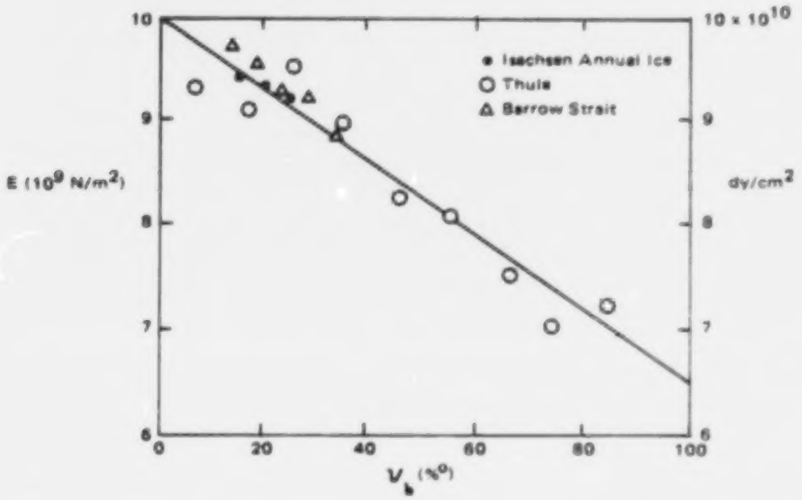


Figure 3.17 Elastic Modulus of Cold Arctic Sea Ice as Determined by Small Specimen Tests Versus Brine Volume (Langleben and Pounder, 1963)

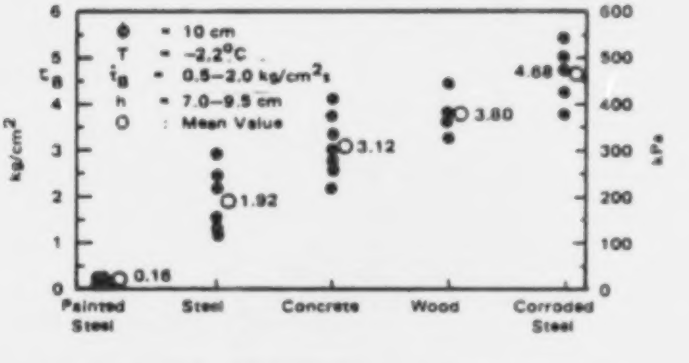


Figure 3.18 Adhesion Strength τ_B for Various Materials

3.2.3.2 Poisson's Ratio

Poisson's ratio is defined as the ratio between the strain in two directions perpendicular to each other in simple tension. Murat and Lainey (1982 - Vol. 2, Appendix 2) measured Poisson's ratio under various stress and test speed rates and found values of 0.5 and 0.35 to 0.40 for low stress and high test rates. They discovered that high rate values decreased with temperature from 0.40 at -5°C to 0.37 at -30°C and -40°C.

The value of μ also appears to vary with the structural orientation of columnar ice. Wang (1981 - Vol. 2, Appendix 2) found that salt water ice was much stiffer in a direction parallel to the basal planes of columns (vertical) than in the perpendicular direction (horizontal) and resulted in a range from 0 to 0.2 vertically and 0.8 to 1.2 horizontally.

As long as ice deformation remains elastic, Poisson's ratio can be considered constant with a value of 0.3. With lateral confinement and plastic deformation Poisson's ratio increases to values of 0.8.

3.2.3.3 Thermal Expansion and Other Properties

The coefficient of thermal expansion of fresh water ice decreases slightly with decreasing temperature: the average value being 5×10^{-5} ($°C^{-1}$). The thermal expansion coefficient of salt water ice is similar to that of freshwater ice although much more variable and complex as a result of the variability of crystallographic brine entrapment at variable freezing rates combined with brine crystallization at various temperatures.

The density of salt water ice is relatively constant with typical values ranging from 0.88 to 0.91 g/cm^3 depending upon the porosity of the ice.

3.2.4 Adhesion and Friction

Adhesion forces primarily occur when an ice field adfreezes to a structure and by horizontal and vertical movement of the ice field causes considerable forces to be transferred to the structure. It is therefore important to know the ice adhesion strength of various materials in order to determine design strengths and reduce ice loads on marine structures.

Saeki et al. (1981 - Vol. 2, Page 133), found that the adhesion strength of salt water ice to various piles was observed to have peak values at 0.1 to 10 mm/s and with 0.5 to 2.0 $kg/cm^2 \cdot s$ with changes of push out speed and stress rate and increased with ice thickness and decreasing pile diameter and ice temperature. They showed that the adhesion strength of salt water ice to painted steel piles was one tenth to that of steel piles and much lower than the adhesion strength for other materials (Figure 3.18) primarily due to the roughness of the pile materials.

Oksanen (1983 - Vol. 2, Appendix 2) found that brine cells weaken the contact surface between ice and other materials as a result of imperfections at the boundary which act as centers of stress concentrations. This causes a dramatic breakdown in the adhesion strength even at low brine volume which seem to remain at a constant level with increased concentrations (see Figure 3.19).

Static and dynamic friction coefficients for different materials in contact with sea water ice have been reported by Saeki et al. (1979 - Vol. 2, Page 134) and are illustrated in Figure 3.20.

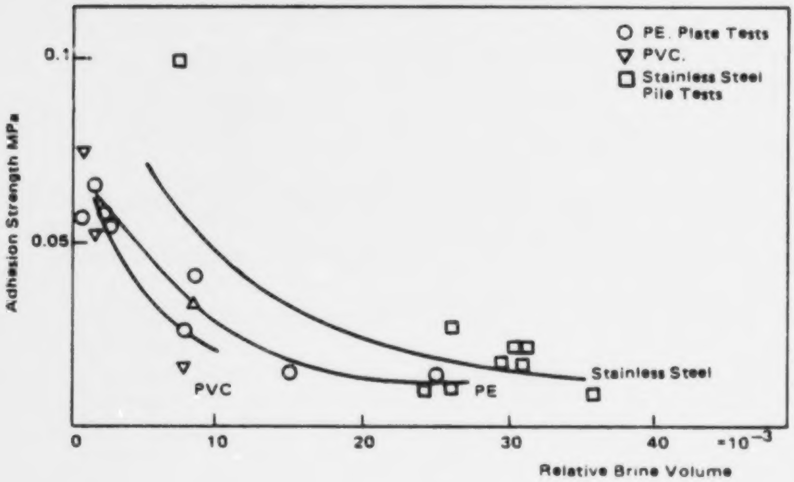


Figure 3.19 Adhesion Strength as a Function of the Brine Volume

3.2.5 Mechanical Properties of Low and Non-Saline Ice

3.2.5.1 Grain Size and Crystal Orientation

Glacier and Estuarine Ice

Very little information is currently available in the public domain concerning the mechanical properties of iceberg ice, however, copious amounts of material concerning glacier ice, from which icebergs develop, has been collected.

As a result of the sedimentation process glacier ice is characterized by a randomly oriented, near isotropic, fine grained material in the upper portions of large ice sheets with crystallographic cross-sectional areas 2 to 5 mm^2.

The flow of glaciers in Greenland through the coastal mountains to outlet glaciers produces strong deformation and recrystallization in the lower sections of the ice sheet. This results in crystals with extremely strong c-axis alignment normal to the plane of

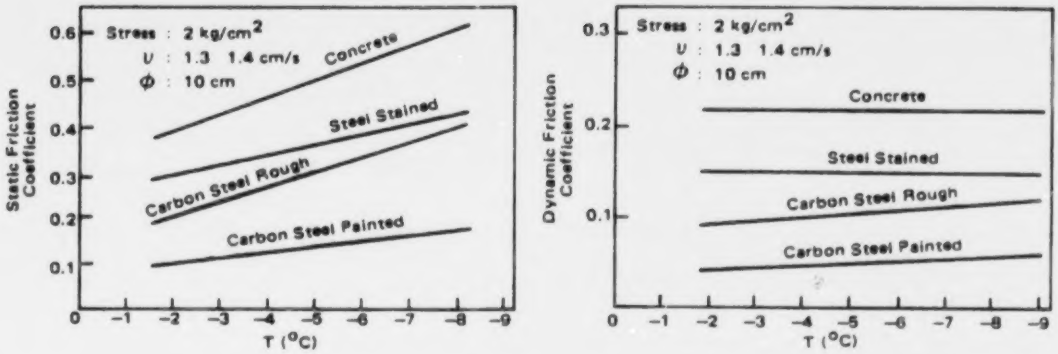


Figure 3.20 Static and Kinematic Friction Coefficients for Ice (Saeki, et al, 1979)

implied shear. Strongly deformed ice in this zone is at or near the pressure melting point (common in temperate glaciers as the Greenland outlet glaciers are classified) and undergoes extensive recrystallization accompanied by an increase in grain size ranging between 100 and 1000 mm^2 (Weeks and Mellor 1983 - Vol. 2, Appendix 2).

In contrast to the roughly equiaxed dimensional crystals commonly associated with ice in the upper layers of the glacier, crystals in the lower strongly deformed ice are much larger and exhibit extremely complex interlocking shapes.

In a recent paper by Gammon et al. (1983 - Vol. 2, Appendix 2) ice samples were collected from five grounded icebergs near St. John's, Newfoundland for crystallographic analysis. Crystal grains were found to be extremely irregular shaped, weakly interlocking and in some cases exhibited some preferred orientation. Grain size diameters of one sample ranged from 14.6 to 33.3 mm.

Estuarine ice, which in this case is being defined as tabular ice masses from the remnant continental ice shelves of northern Ellesmere Island comprise a complex mixture of granular and columnar non-saline ice and granular and columnar saline ice comparable to multi-year ice. As a result, grain size and crystal orientation are extremely variable ranging from rounded, granular crystals of 1 mm diameters to elongated, columnar crystals with grain sizes of 720 mm.

Multi-Year Ice

Grain size and crystal structure of multi-year ice is also highly variable as a result of horizontal layering which reflects the passage of each growth and melt season. The layer formed in the growth season is columnar and exhibits a similar grain size and crystal orientation to first-year sea ice. The melt season layer is thin (2 to 10 mm) exhibits a decrease in grain size (1 to 5 mm) and can have equiaxed to slightly elongated crystal shapes with a random to general c-axis horizontal orientation.

Also there is some indication that recrystallization in the above water level portion of thick multi-year floes occur when brine inclusions are drained from the ice. These inclusions are probably filled with low salinity melt water during the melt season and create an ice floe with a much more complex granular structure.

3.2.5.2 Porosity

Glaciers and Estuarine Ice

The compression weight of overlying snow in a glacier creates a sintering process which bonds snow crystals together and traps air. As a result glacier ice contains many air bubbles which decrease in size with grain growth and increased overburden pressure to a density of 910 kg/m^3. Deformation of ice with glacial flow develops air bubbles with a preferred orientation creating ice with a large range of air bubble content and distribution.

Gammon et al. (1983 - Vol. 2, Appendix 2) found air bubbles in iceberg samples with dimensions of a few tens of a mm and densities of a few hundred per cubic cm. The bubbles were normally round or ellipsoidal and often showed considerable elongation. The air trapped in the bubbles was under compression and reflected the pressure which accompanied the transformation to glacial ice at depth in the source glacier.

Estuarine ice is characterized by a combination of glacial ice with air porosities similar to icebergs and old salt water ice with brine porosities similar to or less than multi-year ice in the range of 0.0 to 3.5 o/oo.

Multi-Year Ice

Presented in Figure 3.21 is the average multi-year salinity profiles for hummocked and depressed areas of multi-year floes. Generally salinities are lowest above the water level and increase with depth to a maximum average of 4 o/oo.

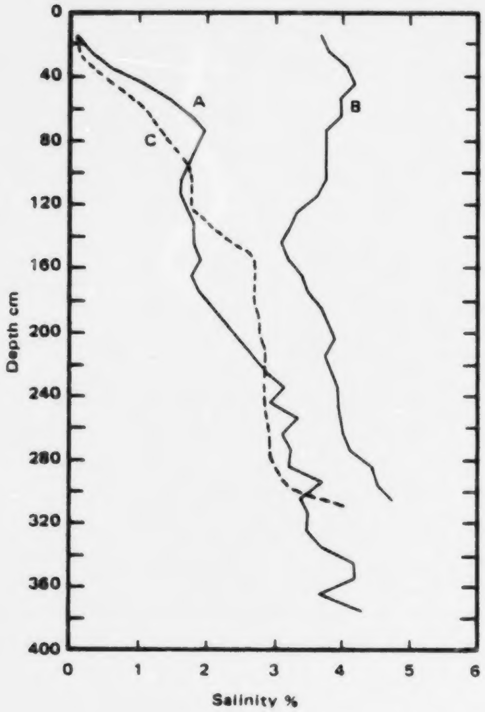


Figure 3.21 Average Multi-year Salinity Profiles for Hummocked (Curve A) and Depressed (Curve B) Areas. Curve C is the Average Multi-year Salinity Profile Determined on Station Alpha by Schwarzacher (1959) (From Cox and Weeks, 1975)

3.2.5.3 Strain or Stress Rate

As previously described deformation resistance and strength increase with an increase of imposed strain rate. Conversely, strain rate increases with an increase of imposed stress. In both cases, $\dot{\varepsilon}$ or σ^n, where n might range from 2 at very low stress (<0.01 MPa) to 4 at high strain rates ($>10^{-3}$ s^{-1}).

Mellor (1979 - Vol. 2, Appendix 2) in a completion of tests on glacier ice at -5°C found that at low strain rates of 10^{-7} to 10^{-6} s^{-1} an initial yield stress point became equal to or greater than the secondary yield stress point. At higher strain rates he found that the initial yield point dominates and becomes the only identifiable yield point. Figure 3.22 shows the effect of strain rate on the yield strength of glacial ice.

Stress-strain relations of low rate ductile yield glacial ice at various temperatures is presented in Figure 3.23.

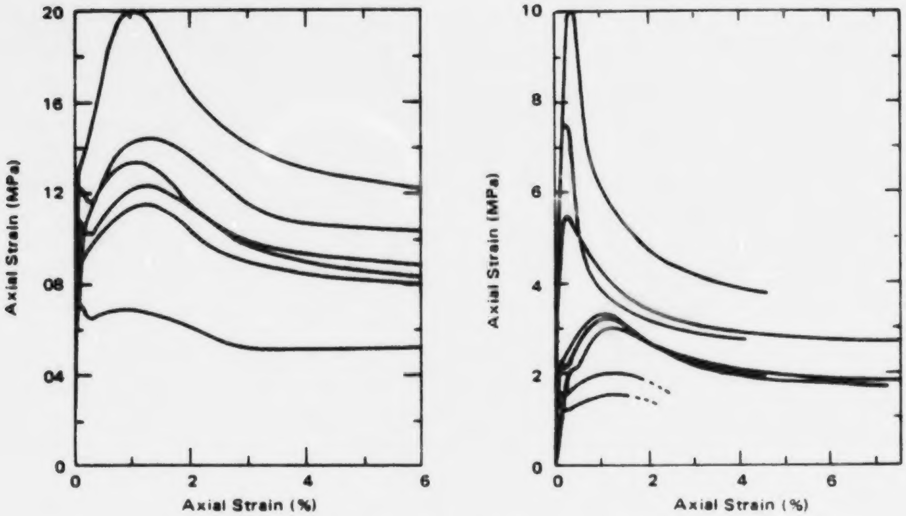


Figure 3.22 Effect of Strain Rate on Yield Strength

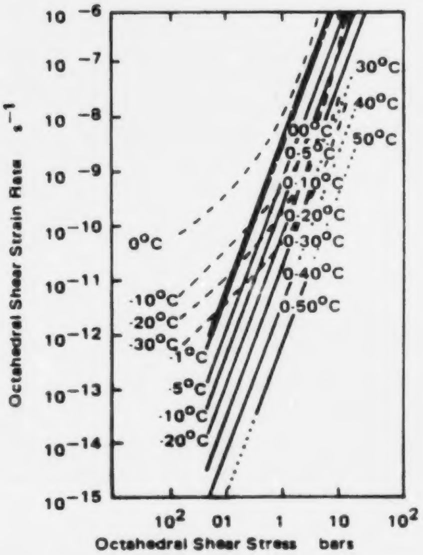


Figure 3.23 Stress/Strain Rate Relations for Creep of Glacier Ice

In comparison studies in which icebergs have been compared to fresh water ice and multi-year ice has been compared to first-year salt water ice, icebergs have exhibited a more ductile fracture resistant behaviour than the more brittle lake ice. It is felt that the air porosity of icebergs is the major factor inhibiting fracture propogation. Multi-year ice generally exhibits a much more brittle behaviour at similar strain rates than does first-year salt water ice and frazil. This is primarily a result of the lower brine and air porosity content of multi-year ice.

3.2.5.4 Temperature

The influence of temperature on the mechanical properties of fine grained, polycrystalline ice similar to polar glacier ice has been studied by Hawkes and Mellor (1972) and Haynes (1979) as well as others. (Vol. 2, Appendix 2). They found that the uniaxial compressive strength is very sensitive to temperature (Figure 3.24). For strain rates of about 1.5×10^{-1} s^{-1} and 2.0×10^{-3} s^{-1} the strength increased about one order of magnitude as the temperature decreased from -0.1°C to -54°C. The average rate of increase for the 1.5×10^{-1} s^{-1}tests was 0.78 MPa/°C. For the 2.0×10^{-3} s^{-1} tests the average rate of increase was 0.6 MPa/°C between -3°C and -35°C. The results indicate that the strength increased about 2-1/2 times between -0.1°C and -3°C for the 2.0×10^{-3} s^{-1} tests.

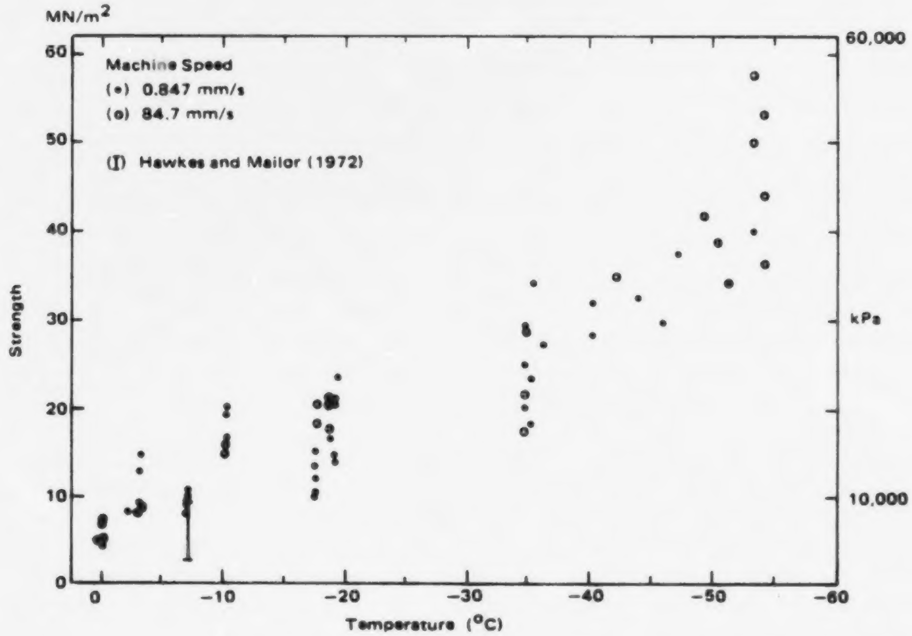


Figure 3.24 Compressive Strength of Low Salinity Ice as a Function of Temperature

The uniaxial tensile strength was not very sensitive to temperature at these high strain rates, but did continue to increase with decreasing temperature (Figure 3.25). The tensile strength increased the most between -0.1°C and -3°C.

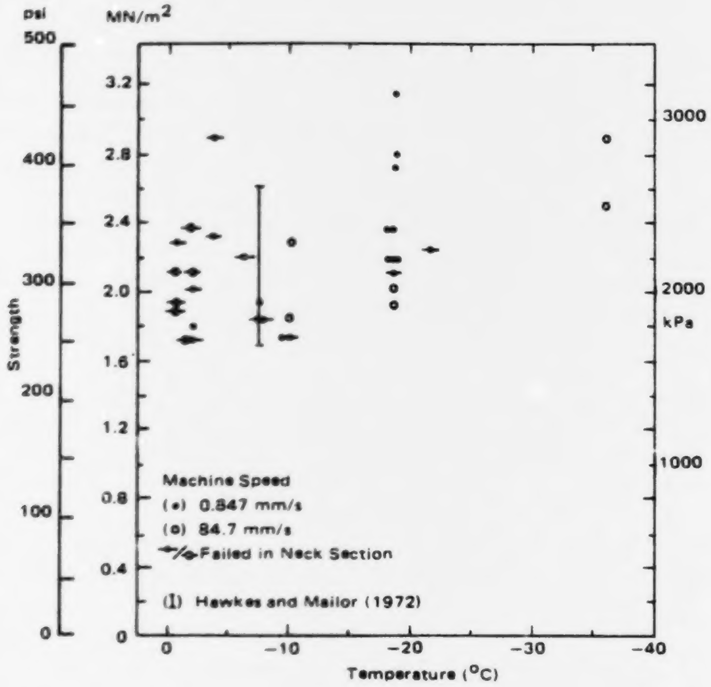


Figure 3.25 Tensile Strength of Low Salinity Ice as a Function of Temperature

3.2.6 Strength Properties of Low Salinity Ice

3.2.6.1 Compressive Strength

The uniaxial compressive strength of low salinity ice types varies with strain rate temperature and porosity. It varies for non-saline ice at -5°C to -10°C by three orders of magnitude (0.01 to 10 MPa) as strain rate varies from about 10^{-11} to 10^{-2} s^{-1}. Gammon et al. (1983 - Vol. 2, Appendix 2) found iceberg ice at -5°C had an uniaxial compressive strength at failure which averaged 5.3 MPa at a strain rate averaging 10^{-3} s^{-1}. Sinha (1984 - Vol. 2, Appendix 2) found that the compressive strength of multi-year ice average 2 to 4 MPa at strain rates between 10^{-5} and 10^{-4} s^{-1}, when loaded in the horizontal plane.

At high strain rates compressive strength is not highly sensitive to temperature whereas at very low strain rates, the variation with temperature can be deduced from the dependence of minimum creep rate on temperature.

At high strain rates compressive strength decreases as porosity increases (density decreases) as shown in Figure 3.26. For low strain rates the effect of porosity is more indirectly related.

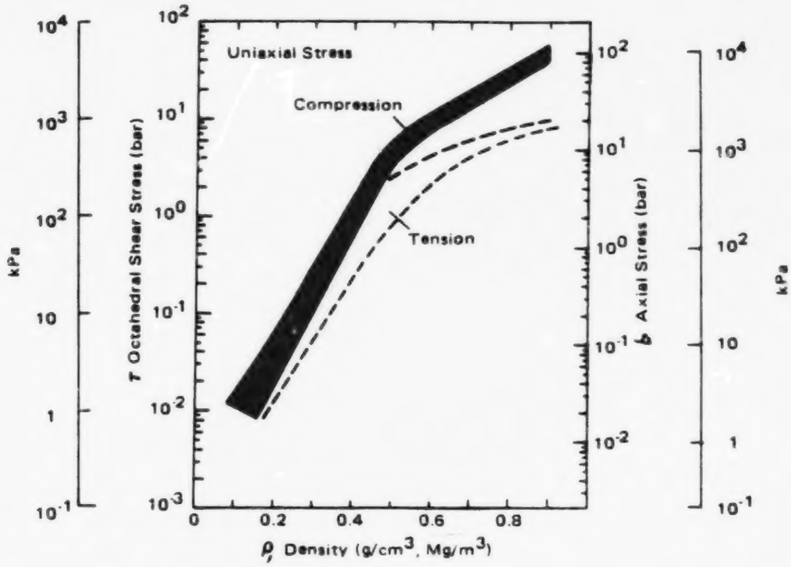


Figure 3.26 Summary of Data on the Strength of Non-Saline Ice and Snow (fr. Weeks and Mellor, 1983)

Grain size does not appear to affect compressive strength systematically at strain rates lower than 10^{-4} s^{-1}. At high strain rates compressive strength is expected to decrease as grain size increases perhaps with $\sigma_c \propto d^{-1/2}$, however, adequate data is not yet available.

3.2.6.2 Tensile Strength

At low strain rates (($<10^{-7}$ s^{-1}) there is little difference between tensile and compressive strength for isotropic ice. In both cases the ice yields by shearing, and the difference of normal stress does not seem to have much effect. Above some critical strain rate (10^{-6} s^{-1} at -7°C - Figure 3.27) there is a bifurcation in the stress/strain-rate curves for tension and compression, presumably because internal microcracks can form and influence the failure at high rates. At high rates ($>10^{-5}$ s^{-1}), tensile strength tends to a limiting value, while compressive strength continues to increase. For the fine-grained ice at -7°C, the high rate limit of tensile strength is about 2 MPa, with compressive strength around 10 MPa.

The effect of temperature on σ_t is the same as its effect on σ_c at low strain rates. By contrast, the lack of sensitivity to strain rate at very high rates leads to the expectation that there will be a corresponding insensitivity to temperature at the range.

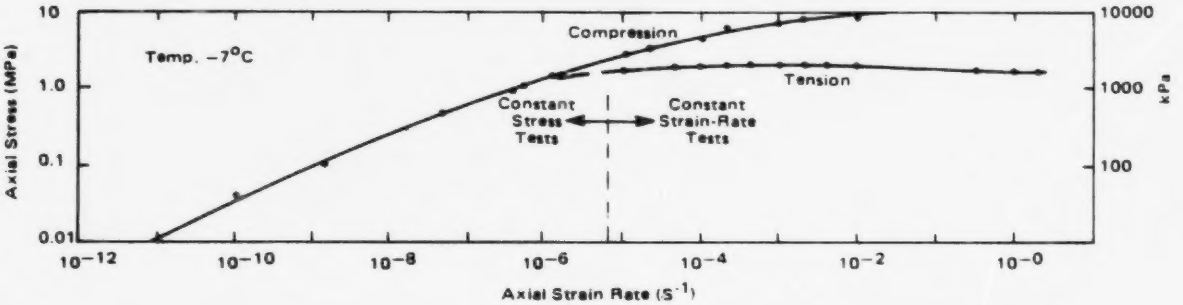


Figure 3.27 Effect of Strain Rate on Compressive and Tensile Strength for Fine-Grained Non-Saline Ice (From Hawkes and Mellor, 1972)

Like compressive strength, tensile strength decreases with decreasing density (increased air porosity) at high strain rates.

The grain size d has a considerable influence on σ_t at moderate strain rates (10^{-6} s^{-1}). The effect can be described by the Hall-Petch relation:

$$\sigma_t = a + b\ d^{-1/2} \qquad (3.27)$$

where a and b are constants (Currier and Schulson 1982 - Vol. 2, Appendix 2). This type of behaviour is expected to prevail at strain rates higher than 10^{-6} s^{-1}, but at very low strain rates d may not have much effect. For practical purposes the value σ_t = 2 MPa for fine-grained ice can be regarded as an upper limit. More coarse-grained non-saline material that is encountered in glacier ice, lake ice, and old sea ice will usually have tensile strength much lower than 2 MPa (typically 1 MPa or less).

3.2.6.3 Flexural Strength

Gow (1977 - Vol. 2, Appendix 2) completed flexural strength tests on fresh water ice and found that lower temperature structurally unmodified ice under simple supported, centre loaded modes averaged from 0.6 to 1.2 MPa (Figure 3.28).

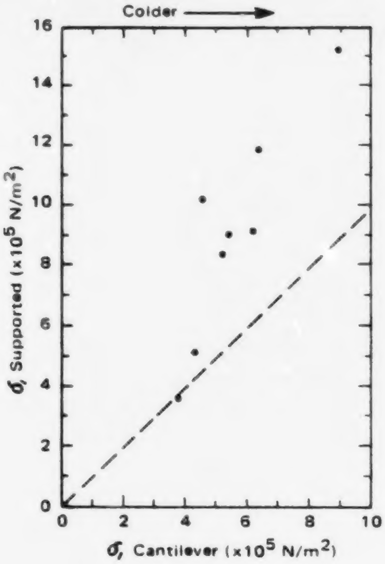


Figure 3.28 Average Values of Flexural Strength of Lake Ice as Determined from Tests on In-Place Cantilever and Simply Supported Beams (fr. Gow, 1977)

This author is not aware of any flexural strength tests which may have been completed on glacier or multi-year ice. It would appear, however, that multi-year ice would have results similar to fresh water ice with a low degree of impurities. With the presence of entrapped bubbles in icebergs and the resultant lower density flexural strength tests might react in more of a ductile nature, more similar to fresh water ice at higher temperatures.

3.2.6.4 Fracture Toughness

The fracture toughness concept is applicable to ice under elastic/brittle conditions, but is irrelevant when rates and temperatures are such that ice yields by flow and recrystallization rather than by nucleation and crack propagation. The critical intensity crack extension, typically used to measure fracture toughness, can be interpreted by elastic theory at high rates and low temperature but such assumptions become worse as rates and temperatures produce greater ductility.

Where ice is elastic and brittle, K_{IC} should be predictable from Young's modulus E ($\approx$ 10 GPa) and the specific surface energy γ ($\approx 0.1 \text{ J/m}^2$). For plane stress:

$$K_{IC} \, (2E\gamma)^{1/2} \approx 45 \text{ kN-m}^{-3/2} \qquad (3.25)$$

Measured values of K_{IC} do appear to have a lower limit close to this value. More typical measured values are around 100 $\text{kN-m}^{-3/2}$, implying that γ_p, the specific energy for plastic working of Orowan/Irwin theory, is about 5γ.

Liu and Miller (1979 - Vol. 2, Appendix 2) and Urabe and Yoshitabe (1981 Vol. 2, Appendix 2) have shown that the K_{IC} increases as test temperature and rate of loading decreases for fresh water ice at high testing rates. Much additional work is required to investigate these trends for a wider range of temperatures and strain rates and with regard to glacial and multi-year ice.

3.2.7 Deformational and Shear Properties of Low and Non-Saline Ice

3.2.7.1 Elastic Modulus

For polycrystalline ice of low porosity (density $\rho \approx 0.917 \text{ Mg/m}^3$), high frequency dynamic measurements of Young's modulus E give values of approximately 9.0 to 9.5 GPa in the temperature range -5 to -10°C. As temperature decreases, E increases non-linearly (Figure 3.29), but the effect is small for "true" Young's modulus (as opposed to "effective" values of E which include creep effects). Porosity n, which can be expressed alternatively as bulk density ρ, has a significant influence on E and it is interesting to note that E drops sharply below the density which represents close-packing of equant grains ($\rho \approx 0.55 \text{ Mg/m}^3$).

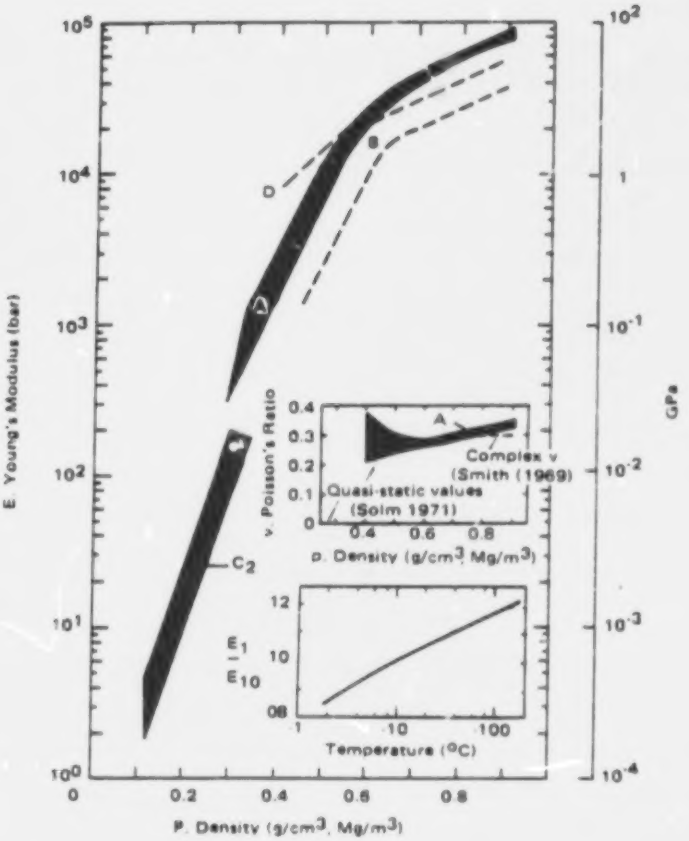


Figure 3.29 Summary of Young's Modulus Data for Non-Saline Ice and Snow (for Data Sources see Mellor, 1974)

3.2.7.2 Poisson's Ratio

Poisson's ratio μ, as measured by dynamic tests, has values close to 0.3 for non-saline ice of low porosity (Figure 3.29), and there is not much variation with porosity over the range where the material is regarded as "ice" rather than "snow" $\rho > 0.8$ Mg/m³).

3.2.7.3 Other Properties

The bulk density of glacial ice varies from 830 kg/m³ to 910 kg/m³. This range is controlled by the overburden compressive pressure of the overlying snow and ice. As this weight increases air bubble diameter decreases and bulk density increases.

Multi-year ice can have a bulk density ranging from 850 kg/m³ to 940 kg/m³ depending upon the location of the sample in the profile and temperature. A hummocky section may be exposed to considerable brine drainage over several years. These channels, if left open, result in ice with a low density. Conversely, depressions go through several freeze and thaw seasons so that all drainage channels become filled and under cold ice temperatures result in high ice densities.

3.2.8 Adhesion and Friction of Low and Non-Saline Ice

The work of Barnes et al. (1971), Evans et al. (1976) and Oksanen (1981 - Vol. 2, Appendix 2), presents results of friction of fresh water ice and theories explaining the results. Rate, temperature, material and contact load can influence the results. The coefficient of friction for fresh water ice can be in the range 0.01 to 0.1, dependent on the above mentioned factors. Some results on friction of sea ice for several materials are summarized in Table 3.2. They show that generally the friction coefficient of sea ice is higher than that for fresh water ice.

Measurements of adhesion of fresh water ice to a number of different materials is summarized in Table 3.3. It can be seen that ice adhesion to low contact angle materials (wood, metals, concrete) is higher than to high contact angle materials such as polymers. In general, adhesion is greater for ice with minimal or no salinity than ice with a higher brine porosity. Adhesion also increases with loading rates.

	Friction Coefficient			
Investigator	Static	Kinetic	Test Material	Test Temperature
Enkvist (1972)			Brackish Ice - (0.9 o/oo)	-5
		.025-.045	Smooth Steel	
		.11	Rough Steel	
			Snow -	
		.09 -.19	Smooth Steel	
		.31	Rough Steel	
			Wet Snow -	
		.03 -.10	Smooth Steel	
		.14	Rough Steel	
Finke (1972)		.045-.065	Sea Ice - Steel	-4.5
Airaksinen (1974)	.4-.7	.07 -.25	Sea Ice - Steel	-
Grothues-Spork (1974)	.3-.5	.12 -.23	Sea Ice - Steel Cone	-7

From: Frederking 1983

Table 3.2 Friction Coefficients

Material	Temperature (°C)	Adhesion Strength kPa	Source
PVC	-2.5 to -3	65	Frederking & Karri
(1981)			
PE	-2 to -3	59	
Concrete	-1 to -3.5	440	
Wood	-2 to -4	470	
Steel	-1 to -3.5	480	
Wood	-6	1380	Parameswaran (1981)
Concrete	-6	840	

From: Frederking, 1983

Table 3.3 Measured Adhesion Strength of Some Materials to Ice

3.2.9 Unconsolidated and Reformed Ice

In the fragmentation process, various types of ice are created. Weeks and Mellor (1983 - Vol. 2, Appendix 2) describe fragmented ice as follows:

> Fragmented ice covers a broad spectrum, from fine grained mush ice, through blocky brash ice, up to fine ice, rafted ice and ridged ice.
>
> Mush ice is something like waterlogged snow, with fluid properties while it is floating freely, and high cohesion when it is compacted or drained. Data are not available for this type of ice.
>
> Brash ice has more or less equant particles in the size range 0.02 to 2.0 m. The tendency has been to treat it analytically as granular "c-ϕ" material that conforms to a Mohr-Coulomb failure criteria, but for horizontal penetration of a uniform layer the stress-free upper and lower boundaries appear to permit yielding in conformance to a criterion of the Von Mises type.
>
> Large ice blocks pushed together into pressure ridges also form a "granular" material which initially has cohesion "c" and internal friction (shear resistance) "ϕ". The scale of this material is too big for conventional measurements of its bulk properties, but some deductions can be made from analysis of natural processes."

The properties of fragmented ice are summarized in a paper by Mellor (1983 - Vol. 2, Appendix 2).

3.3 Regional Ice Characteristics

3.3.1 Beaufort Sea

The Beaufort Sea is essentially ice covered for about 9 months of the year. It is comprised of three dynamic ice zones; the landfast, the transition and the polar pack zone (Figure 3.30, Kovacs and Mellor 1974 - Vol. 2, Appendix 2). An excellent review of Beaufort Sea ice conditions and dynamics appears in Volume 3A of the Beaufort Sea Production Environmental Impact Statement (1982) and in Ice Engineering I, a paper presented by R. Frederking at the Offshore Mechanics and Cold Region Engineering Symposium, June 13, 1983.

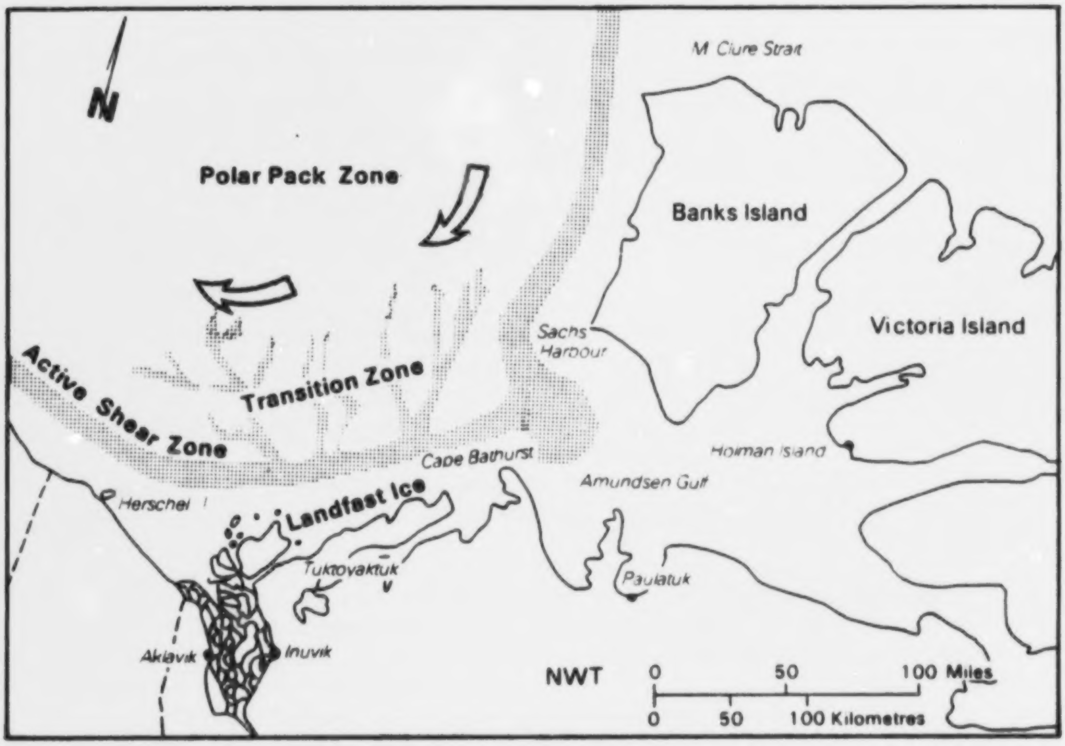

N
M Clure Strait
Polar Pack Zone
Banks Island
Victoria Island
Sachs Harbour
Active Shear Zone
Transition Zone
Cape Bathurst
Holman Island
Amundsen Gulf
Herschel I
Landfast Ice
Tuktoyaktuk
Paulatuk
Aklavik
Inuvik
NWT
0 50 100 Miles
0 50 100 Kilometres

Figure 3.30 Winter Ice Zones of the Southern Beaufort Sea (From Kovacs and Mellor, 1974)

The landfast ice zone is immediately adjacent to the coast and effectively fixed to it. The ice cover in this zone is primarily first-year ice although occasionally multi-year ice from the polar pack may be incorporated. Growth initiates at the shore in late September or early October and progresses seaward. Up to a water depth of 5 m the ice surface is essentially smooth. Further from shore the ice cover may be broken up by late season storms and forced into ridges. As the ice becomes thicker the landfast ice edge moves outwards. For water depths 13 m and greater ridges are formed with sufficient sail height and keel depth that they can ground on the sea bottom. This zone of partially grounded ice extends to the 20 m water depth contour which approximately delineates the outer edge of the landfast ice zone. The occurrence of ridges increases with distance from shore reaching frequencies greater than 12 ridges per kilometre in the grounded zone. Ridges in the landfast zone typically have sail heights 0.75 to 1.5 m, although extreme heights of 10 m have been observed. Once the landfast ice reaches its maximum extent the position of its outer edge does not change substantially. The level undeformed ice cover reaches a maximum thickness of approximately 2 m by the end of April. Break-up and clearance of ice starts in May from the shore and by mid-July to early August the landfast zone is clear of ice. Last to break out is a bridge of ice extending from Cape Bathurst to Herschel Island. The landfast ice zone remains relatively stable throughout the winter period.

Movements are in the order of metres with typical movements of less than 1.5 m occurring over a time interval of an hour.

The transition or shear zone extends from the edge of the landfast ice to the polar pack and accommodates the relative movement between the fixed landfast ice and the constantly rotating polar pack. Its width can vary from a few kilometres to 300 km depending on geographic location and the position of the polar pack. This variation occurs seasonally and from year to year. The transition zone comprises mostly first-year ice but may also contain some multi-year ice. The interaction of ice in this zone is a result of the northward growth of first-year ice from the landfast zone meeting the southward growth of first-year ice from the polar pack.

Ice movements in the transition zone are highly dynamic and continue throughout the winter. Average speeds range from 3 to 13 km/day with maximum speeds occurring in September and minimum speeds in February and March. Maximum movement rates of 30 km/day have been observed. Net ice movement in the transition zone is from east to west. Ice conditions in this zone are extremely variable. Highly deformed hummock fields may be present as well as areas of thin ice. A flaw lead as much as 50 km wide, depending on wind direction, may form adjacent to the landfast ice edge. Because of the highly dynamic nature of the transition zone first-year ridges are a common feature of it. They increase in number during the winter, reaching a maximum in about February. Their frequency and distribution is highly variable. Break-up of the transition zone actually precedes that of the landfast ice zone. It generally begins in June with the extension of the flaw lead and the Cape Bathurst Polynya and gradually proceeds northwards reaching a maximum extent in September.

The polar pack is the zone of permanent multi-year ice covering the Beaufort Sea and the Central Arctic Basin. The part of the polar pack of interest here circulates clockwise in the Beaufort Gyre which is centred about 76°N, 145°W. The outer edge of the Gyre has a mean drift speed of about 2 km/day (2.5 x 10^{-2} m/s) although there may be large local variations depending upon wind patterns. The southern boundary of the polar pack generally lies at about 72°N.

The polar pack also contains some leads and first-year ice. The first-year ice can have thickness of up to 2 m and the multi-year ice ranges in thickness from 2 to 4 m. The main interest in the polar pack is as a source of multi-year ice for the coastal zone in the Beaufort Sea and a northern limit for offshore operations.

During the open water season, it is possible for massive ice features, such as ice islands, multi-year floes and hummock fields to enter the landfast zones and impact offshore structures. As a result of their deep drafts such features usually become grounded before impacting coastal structures.

3.3.2 Arctic Archipelago

First-year ice in the Arctic Archipelago grows from a thickness of about 60 cm in late November to an undisturbed thickness of about 1.5 m by early February. Rafting creates ridges in some areas up to 15 m thick. In amongst the first-year ice cover there are numerous multi-year floes. These drift southward from the polar pack and range in thickness from 2 to 30 m. Some multi-year fragments also originate from annealed ridges and glaciers.

Ice concentrations vary through the year. During January to April, ice cover is nearly 100% except for the occasional open water lead caused by currents or winds. With spring break-up, the ice cover decreases gradually to a minimum concentration around September.

Many areas of the Arctic Islands are covered year-round with multi-year ice, with leads opening between in the summer. The surface of this ice is very rough, hummocks of 1 to 2 m being common. These hummocks are usually weathered and not as jagged as newly formed hummocks and ridges. Ridge fragments from years past can often be detected as a linear hump across a floe.

3.3.3 Hudson Bay

The Hudson Bay region is entirely covered by first-year ice. By late October a thin layer of ice covers the inlets and has started to build seaward from the coastline. Average winds of 24 to 30 km/hr. and extreme winds of 80 to 100 km/hr. during October, November and December create extensive dynamic ice movement and the formation of pressure ridges and rafted ice features during the early stages of ice formation. Except for fluctuating shore leads and wind induced patches of open water kilometres from shore. By late spring ice measurements vary from 145 cm thick in the south to 180 cm thick in the most northern sections of the surface of Hudson Bay is covered by ice by mid-December. Ice breakup in Hudson Bay begins in late May with pack ice over the bay and Hudson Strait presenting an effective barrier to shipping until July.

3.3.4 Baffin Bay

The major factors controlling the ice regime in Davis Strait and Baffin Bay are the relatively warm, north-flowing Canadian West Greenland Current on the eastern side, the cold south-flowing Canadian current to the west, and a major polynya, the "North Water", in the northern part of Baffin Bay. The warm West Greenland Current retards ice formation in eastern Davis Strait and results in an earlier break-up along the coast from southern Davis Strait to Disko Island. Conversely, the Canadian Current results in earlier ice formation along the Baffin coast, delayed break-up there, and an extension of ice-covered waters and the presence of icebergs far south of Davis Strait.

Baffin Bay in winter consists of a rafted and ridged mixture of first-year and multi-year ice intermixed with icebergs. First-year ice begins to form in mid to late October and grows from the coastline seawards and from the multi-year flows outward. By November most of Baffin Bay is covered by a thin layer of first-year ice. This ice layer persists, reaching a maximum undisturbed thickness of 2 m by March. Break-up of the first-year ice pack begins in June spreading out from the north open water polynya at the northern tip of Baffin Bay.

Multi-year ice is present in various concentrations in Baffin Bay throughout the summer melt period. Multi-year floes originating from the polar pack drift into Baffin Bay via Lancaster, Jones and Smith Sounds, and drift along the Baffin Bay and Labrador coastlines in the cold southerly current.

Baffin Bay is located in the largest iceberg calving zone. An estimated 150 to 200 km^3 of icebergs separate from the glacier complexes along the west Greenland coast each year. These icebergs drift north to the northern part of Baffin Bay and return south on the cold Labrador current grounding along the Baffin Bay-Labrador coastline and become frozen into the ice during the winter period. In late spring - early summer these icebergs and large pack ice floes drift southward creating extreme hazards to offshore structures.

3.3.5 Labrador Shelf

Sea ice dynamics in the Labrador Sea are influenced by the interplay of the Labrador current, local wind and the wave climate of the North Atlantic. The Labrador Shelf, the area of interest for petroleum exploration, extends out about 300 km to water depths of about 1000 m. The Labrador current moves parallel to the Labrador coast in a southeasterly direction at a velocity of about 0.2 m/s (Beringer and Wright 1980 - Vol. 2, Appendix 2). The ice in the Labrador Sea can be divided into three zones; a landfast zone bounded by the shore on one side and a shear polynya on the other, an interior zone, and a marginal ice zone.

Landfast ice forms initially in sheltered bays along the coast in late November or early December and extends seawards about 25 km at its maximum extent. Level undeformed ice in this zone is 0.5 to 1.0 m in thickness. Icebergs or multi-year ice can be frozen into this ice. At the outer edge of the landfast ice there is a shear zone which accommodates the relative movement between the interior zone and the fixed landfast ice. A polynya from 10 to 25 km wide forms in the shear zone. The width is a function of the geography of the shore line and local winds, so there are times when it can be closed up completely.

The interior zone is transitory, developing only in mid-winter when there is a sufficiently wide marginal ice zone to dampen out swell. This allows quite large floes to survive in the interior zone. Direction of ice movements in this zone is random.

The marginal ice zone may extend 100 to 300 km offshore. It comprises a mix of first-year pack ice, multi-year floes and icebergs. First-year pack ice begins to form in late November. It is highly deformed and by April may in places reach a thickness of 8 m. Multi-year floes and icebergs are incorporated in the pack and move along together with it. The pack is highly dynamic with wide variations in concentration and ice type at any given location or time.

The multi-year floes which originate in areas adjacent to northern Baffin Bay may have masses in the range 10^3 to 2×10^5 tonne with mean thickness of the order of 10 m in the Labrador Sea. Ice movement studies of these floats indicate they drift at an average velocity of 0.1 m/s in a southeasterly direction. Over a short time period of 4 to 8 hours, speeds ranged from 0.05 to 0.5 m/s with a maximum of 1.5 m/s and movement was in all directions (Beringer and Wright 1980 - Vol. 2, Appendix 2).

The number of icebergs in the Labrador Sea is highly variable. Extrapolating from International Ice Patrol data, densities of 3 to 6 bergs per 10^3 km^2 could be expected in the May to July period and 0 to 2 in the October to January period (Gustajtis 1979 - Vol. 2, Appendix 2). Local densities may vary considerably. Size is also highly variable, from 10^3 tonnes to 10^6 tonnes on average and a maximum of 2×10^7 tonnes. The movements of icebergs are primarily in response to current so they are also carried by the Labrador current at average velocities ranging from 0.1 to 0.3 m/s, however, velocities up to 1 m/s have been observed even for large bergs (Beringer and Wright 1980 - Vol. 2, Appendix 2).

3.3.6 Grand Banks

Sea ice forms on the southern coast of Labrador in mid-December and moves south to eastern Newfoundland waters in early January. The normal southern limit of the ice pack is 48°N, just south of St. John's. In years when north or northeast winds are prevalent, the pack may extend to inshore waters as far south as Cape Race in mid-February. From here, the normal drift is southward, as far as 46°N in a new severe winters. Retreat of ice begins in late March and, by the end of April, the southern edge has usually retreated north of Cape St. Francis.

The most critical ice feature problem associated with the Grand Banks area is the normal occurrence of icebergs which drift slowly and erratically southward along the Labrador Current. In an average year about 1200 bergs are monitored moving past 60° latitude with only about 250 passing to the 50° latitude. Figure 3.31(A) gives an indication of the number of sightings over the Grand Banks during a 9 year period.

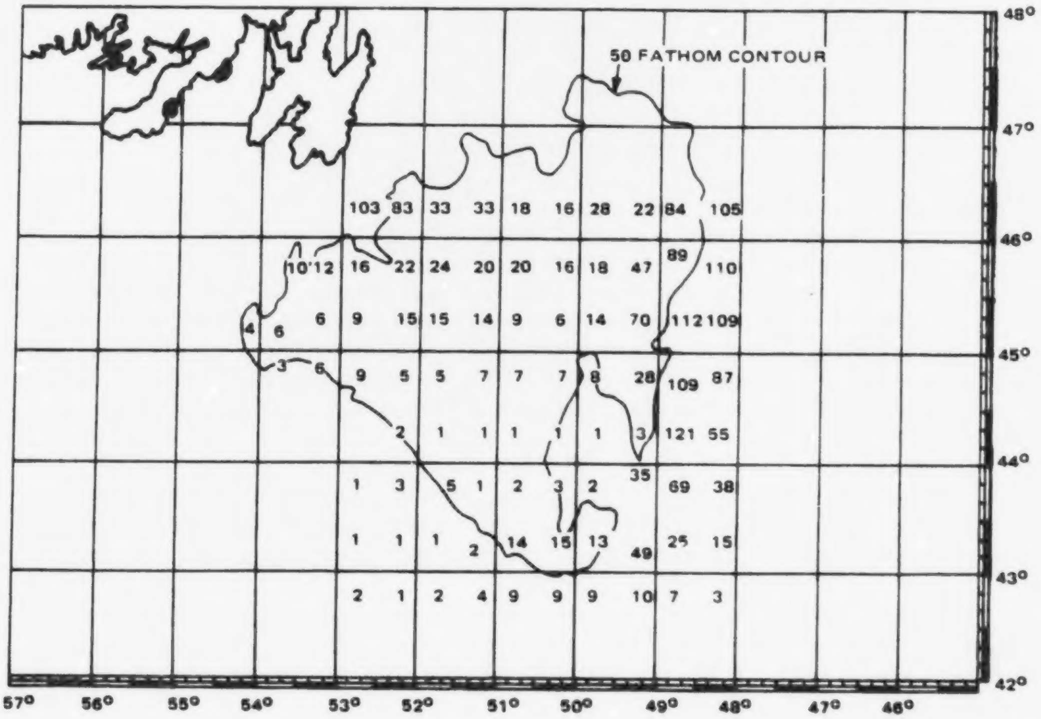

50 FATHOM CONTOUR
48°
47°
46°
45°
44°
43°
42°
57°
56°
55°
54°
53°
52°
51°
50°
49°
48°
47°
46°
103 83 33 33 18 16 28 22 84 105
10 12 16 22 24 20 20 16 18 47 89 110
4 6 6 9 15 15 14 9 6 14 70 112 109
3 6 9 5 5 7 7 7 8 28 109 87
2 1 1 1 1 1 3 121 55
1 3 5 1 2 3 2 35 69 38
1 1 1 2 14 15 13 49 25 15
2 1 2 4 9 9 9 10 7 3

Figure 3.31 (A) Sightings per ½° Rectangle During the 9 Year Period, 1948-1956

The first icebergs usually appear on the northern edge of the Grand Banks in late February or early March. They are most numerous in April, May and June but may be sighted in all months. Up to 700 icebergs are reported to reach 52°N each year, of which about a third move as far south as St. John's. In some seasons, the southward drift of icebergs may be concentrated on the eastern portions of the Grand Banks, while in other years they remain close inshore and may round Cape Race in a westerly direction. The mean and extreme limits of iceberg penetration into the waters of east Newfoundland during the spring months is shown in Figure 3.31(B).

Occasionally during the spring large pack ice floes separate from the ice cover in Baffin Bay and along the Labrador Shelf and drift onto the Grand Banks. These floes can be comprised of a mixture of icebergs, multi-year floes, pressure ridges and rafted ice held together by first-year ice. Such features which may reach dimensions ranging from 10 to 100 km in diameter also present very serious problems to offshore structures.

3.4 Ice-Structure Interaction

3.4.1 Ice Effects at Various Stages of Development

3.4.1.1 Final State Effects

Structures may be exposed to various types of ice forces such as static and dynamic horizontal thrusts, vertical load from weight or downdrag or uplift from water level fluctuations. Depending on the ice region and the structure, either static or dynamic effects could be critical. Characteristic areas where static loads are likely to occur due to thermal stresses are bays and shallow waters. Winds and currents can also set up static stresses in an ice sheet or ice pack. Drifting ice masses could deliver dynamic thrusts on a structure. Vertical loading has caused failures of piled structures from ice bustles on piles at waterline slipping against other piles, and piles have been pulled out under tidal action.

Global ice forces are a danger to the overall safety of offshore structures. Local ice forces can cause damages to structural elements in offshore projects. Ice ride-up to working areas must be considered.

In most arctic waters, shoreline structures, ports and navigation aids are subjected to ice thrust. Pile supported shoreline structures have serious effects from the weight of ice and downdrag and uplift from an ice sheet. Ice ride-up affects sloping faces, as used in ice protection devices and breakwaters. Ice rubble generation can be detrimental because it generates obstacles, creating shore ice mounds. On the other hand, ice rubble can give also a measure of protection to shoreline structures.

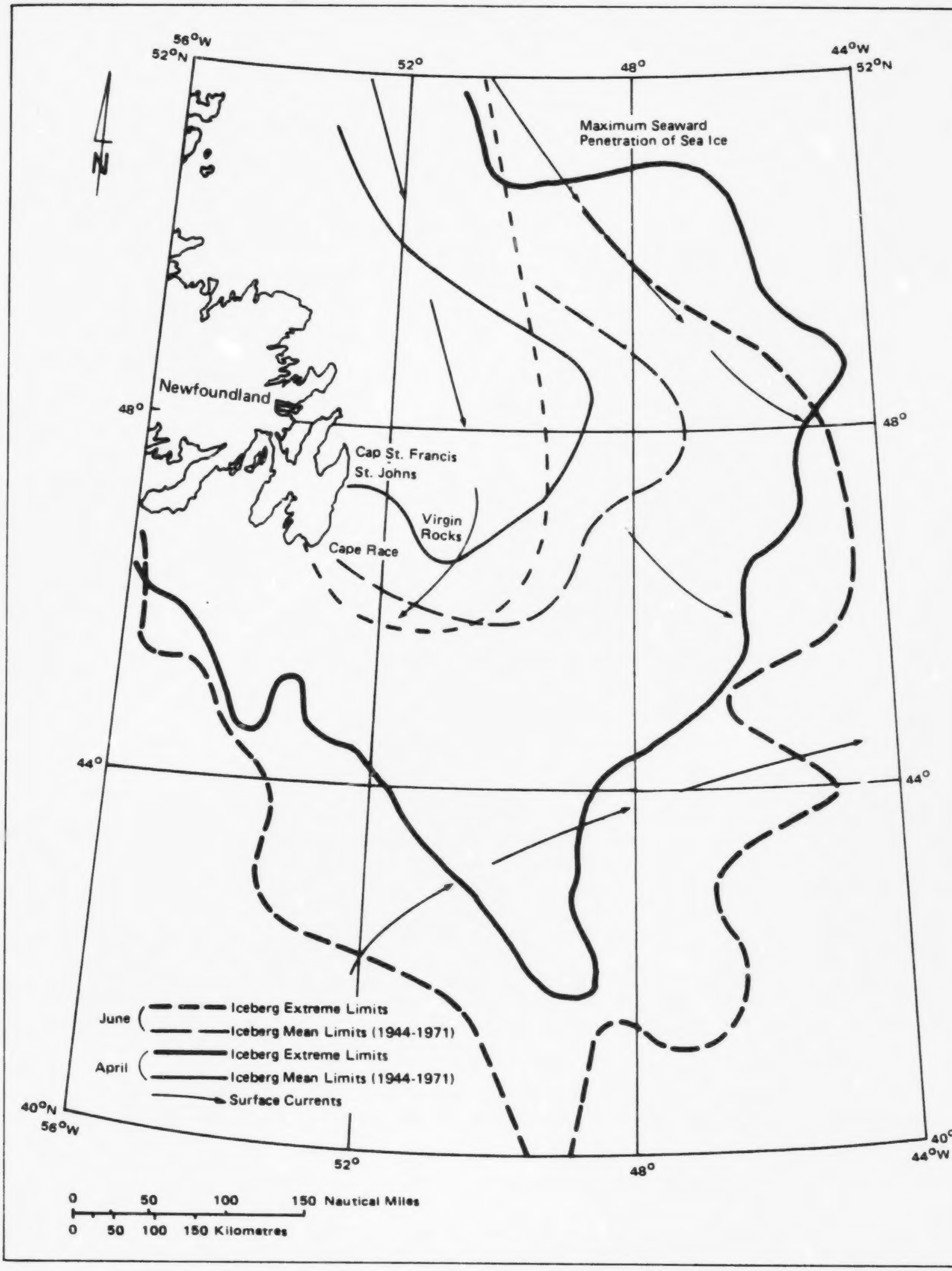

56°W
52°N
52°
48°
44°W
52°N
Maximum Seaward Penetration of Sea Ice
N
Newfoundland
48°
48°
Cap St. Francis
St. Johns
Virgin Rocks
Cape Race
44°
44°
40°N
56°W
40°N
44°W
52°
48°
June
Iceberg Extreme Limits
Iceberg Mean Limits (1944-1971)
April
Iceberg Extreme Limits
Iceberg Mean Limits (1944-1971)
Surface Currents
0 50 100 150 Nautical Miles
0 50 100 150 Kilometres

Figure 3.31 (B) Grand Banks General Surface Circulation and Iceberg Limits

Floating mooring structures are very susceptible to dynamic ice thrust. Also, superstructure icing is a danger for floating facilities.

Access to terminals is governed by ice. This may suggest control of ice by breaking, and mechanical cleaning which could be made part of the design. Icebergs and multi-year ice pose special problems.

Ice scour makes connections to offshore facilities vulnerable from ice conditions. Shore entry problems are particularly difficult to solve.

3.4.1.2 Construction Effects

Short exposure time during construction limits the probabilities of maximum ice forces being applied. A reduced effect can be justified. A selection of an appropriate construction season may permit further reductions in ice force application to structures.

The use of ice for transportation and erection is a factor in the choice of designs and construction methods. Structures can be erected from ice and pipelines can be placed from ice.

Ice is an aid in logistics. Ice roads and ice airstrips are vital in northern construction. Special vehicles, such as rolligons and air cushion vehicles make best use of the bearing capacity of ice.

Operations on the construction site can be aided by a solid ice cover. Equipment can be supported. It is important to define the bearing capacity of natural and built-up ice. The ability of ice to support operations is also limited by the extent of motion and the stability of the ice pack. Therefore these factors must be established.

Ice is a readily available construction material in the arctic. Platforms for work and storage have been made of built-up ice. Both overwater and grounded roads have been built of ice. Loading and transfer islands and at least one construction dock has been built of ice. Ice has provided shelter against elements. Simulation of loads using ice and water has been a part of many test programs. Sheet pile structures and cells rely on frozen earth support to its skin to resist ice forces.

Temperatures can be low enough to affect construction. In the confined areas at construction sites, temperature effects on ice must be considered.

3.4.1.3 Operational Effects

Originally, navigation in Canada was limited to the open water season. Iron and steel hulled ships have extended navigation seasons into ice covered periods. Ice breakers have played a major role in this extension.

The layout of the facility plays a major role in the ability of ships to reach and be berthed at a navigation facility. Repeated breaking and refreezing is a particular problem in arctic channels because of increase in ice volumes caused by this activity.

3.4.1.4 Factors in Ice Hazards

The main factors in engineering design for ice hazards are identified on the logic diagram illustrated on Table 3.4. Ice thrust is the most serious problem to arctic marine structure development.

Each of the factors may be combined with other factors to obtain the most severe ice hazards for the specific application.

3.4.2 Effect of Environmental Conditions on Interaction Forces

Table 3.5 illustrates a logic which may be used in the analytic process to assess the severity of ice forces on a particular site and structure.

3.4.2.1 Thermal Ice Forces

The main factors were described under the heading of the influence of air temperature. A recent thorough review of various methods to estimate temperature ice forces has been carried out by Kjeldgaard and Carstens (Carstens 1980 - Vol. 2, Appendix 2). This publication makes substantial use of a monograph by Drouin and Michel where many aspects are covered in greater detail (Drouin and Michel 1971 - Vol. 2, Appendix 2).

The usual practice in North America for fresh water bodies has been reviewed by the Inland Waters Branch, Department of the Environment (Inland Waters Branch 1971). In this review the thrust may be assumed to vary linearly with the ice thickness at a rate of 240 kPa (5000 lb./sq. ft.). This gives a load of 240 kN/m for 1 m thickness of fresh water ice.

Drouin (Carstens 1980 - Vol. 2, Appendix 2) is of the opinion that, 150 to 300 kN per m be used in Canada for thermal forces from fresh water ice.

In the Soviet Union for the regions of Siberia, Leningrad and Caucasus, Starosolsky (Carstens 1980) recommends 300, 200 and 150 kPa as a first approximation for design purpose.

According to Carstens, conditions in Norway are less severe than in Canada or Soviet Union. In unfavourable circumstances, loads of 150 to 200 kN per m are still recommended.

Table 3.6 has been extracted from Carstens.

Initiation of Arctic Marine Project

Result of Decision:

Following Steps to Execution

Ice Conditions

- Environmental Driving Force
- Transmitting Agent
- Contact Mass

Reusit of Analysis:

Impact Severity and Frequency

Ice-Structure Interaction

- Contact Condition
- Interface Geometry
- Dynamic Structural Response

Result of Analysis:

Ice Interaction Algorithm to Express Interaction Stresses as Time Functions

Ice Attack on Structures

- Ice Damage to Contact Face
- Structural Damage form Ice Thrust
- Loss of Stability from Ice Thrust
- Damage from Vertical Ice Forces

Result of Analysis:

Exposure to Various Types of Ice Damage

Alternative Schemes for Handling Ice

- Ice Resistant Schemes
- Schemes Utilizing Ice
- Schemes with Ice Control
- Schemes Avoiding ice Hazards

Result of Analysis:

Planning and Conceptual Design of the Structure

Arctic Structural Strength, Durability and Compatibility

- Arctic Structural Elements
- Arctic Structural Materials
- Avoiding Environmental Disturbance

Result of Study:

Detailed Design of Arctic Structure

Arctic Marine Design Methods

- Design Requirements
- Methods of Analysis

Result of Analysis:

Verification of Strength and Stability

Execution of Arctic Marine Project

Table 3.4 Factors in Engineering Design for Ice Hazards

Footnotes:

It is assumed above that the extent of the ice cover is less than 50 m otherwise the values should be multiplied by a reduction factor according to SN 76-66.

The question of the type of restraints relevant to the examples given in the table will be considered in more detail:

- Drouin has computed the forces exerted by Monfore ice in the uniaxial case. In connection with a similar calculation Michel mentions that for the biaxial case the results for Monfore ice would be about 60% larger using elastic theory as the first approximation in extending the results from the uniaxial to the biaxial case.

- Referring to the conclusions made by Drouin and Michel, it seems to be in agreement with their train of thoughts to look upon the results of the uniaxial tests with S1 ice as a reasonable estimate of the pressure exerted by biaxially restricted S1 ice as it occurs in nature with some scatter in the directions of the c-axes. Further these results can be taken as a reasonable upper limit of the forces exerted by biaxially restrained S2 ice.

- In the Russian norm SN 76-59 and SN 76-66 no distinction is made between uniaxial and biaxial restraints, i.e. the users of the norm do not have to decide which sort of restraints exist in the actual case.

It is seen from the table that the values computed by means of the SN 76-66 are very dependent on the speed of wind w, i.e. on the thermal boundary layer in air above the ice/snow surface. The later Canadian investigators Drouin and Michel do not attach the same importance to the boundary layer. In fact Michel says that the difference between the temperature of the ice surface and the temperature of the air "is small and measurements made for a whole winter on clear ice have shown that it rarely exceeds 3°F (1.7°C). It is thus safe and acceptable to neglect this effect".

Further Drouin and Michel (1974 - Vol. 2, Appendix 2) give an example of application of their test results for S1 ice. The example is for an air temperature originally at -36°C. To take account of both the effect of the boundary layer and the weak possibility of the initial temperature gradient in the ice being a straight line they assume an initial ice surface temperature of -30°C. No further account is taken of the boundary layer in their example. Thus it seems that the question of temperature distribution above the ice/snow surface is one of the main divergencies between the later methods for computing the ice pressure.

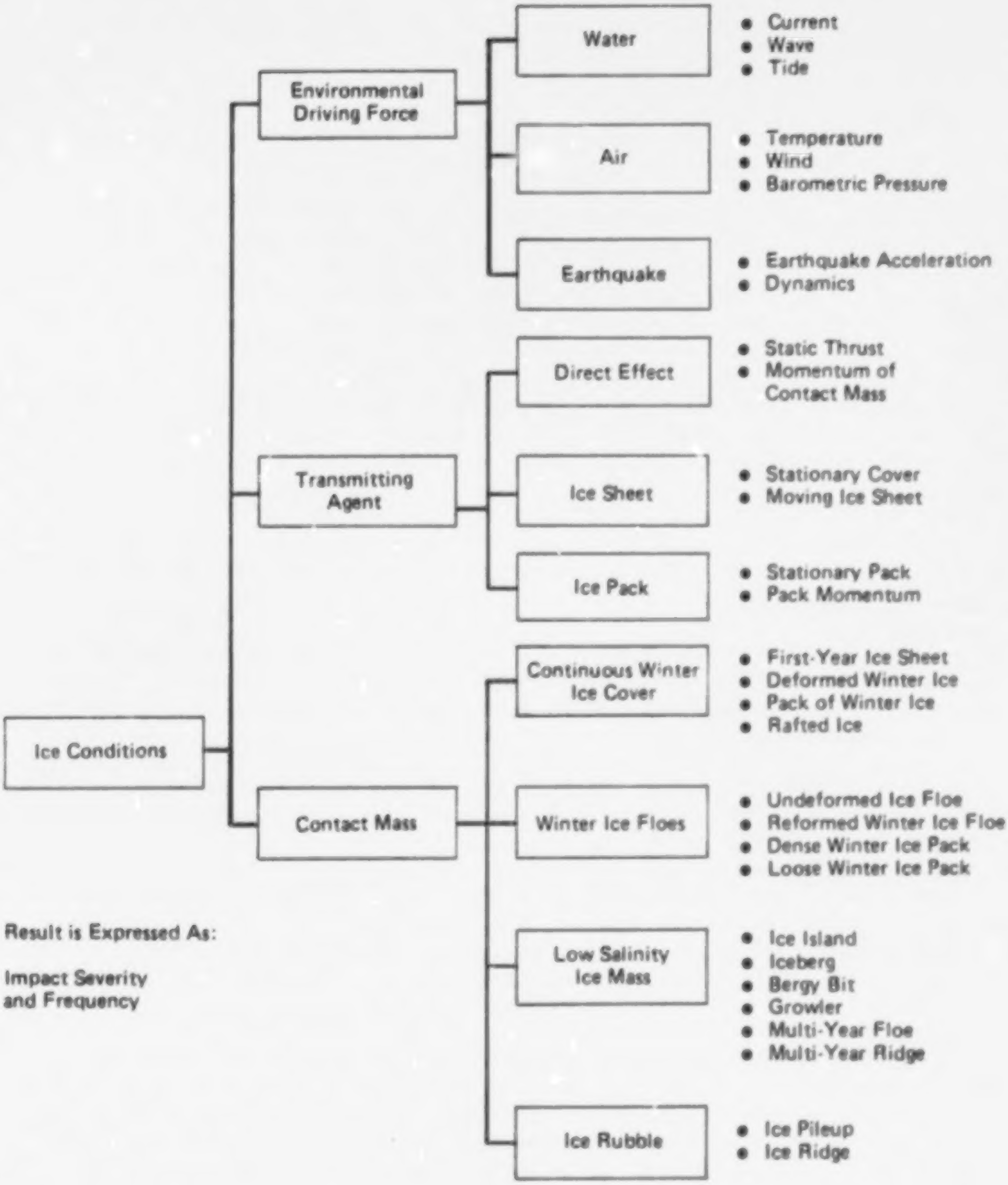

Ice Conditions
Environmental Driving Force
Transmitting Agent
Contact Mass
Water
• Current
• Wave
• Tide
Air
• Temperature
• Wind
• Barometric Pressure
Earthquake
• Earthquake Acceleration
• Dynamics
Direct Effect
• Static Thrust
• Momentum of Contact Mass
Ice Sheet
• Stationary Cover
• Moving Ice Sheet
Ice Pack
• Stationary Pack
• Pack Momentum
Continuous Winter Ice Cover
• First-Year Ice Sheet
• Deformed Winter Ice
• Pack of Winter Ice
• Rafted Ice
Winter Ice Floes
• Undeformed Ice Floe
• Reformed Winter Ice Floe
• Dense Winter Ice Pack
• Loose Winter Ice Pack
Low Salinity Ice Mass
• Ice Island
• Iceberg
• Bergy Bit
• Growler
• Multi-Year Floe
• Multi-Year Ridge
Ice Rubble
• Ice Pileup
• Ice Ridge
Result is Expressed As:
Impact Severity and Frequency

Table 3.5 Logic Illustration to Assess Severity of Ice Forces at a Specific Site and Structure

$T_o = -40°C$, $T_i = 0°C$ $\frac{\Delta T}{\Delta t} = 2.8°C/h$	Ice Force (Kn/m^2) Based on Ice Thickness	
	0.45 m	0.90 m
Rose 1947 (Drouin 70)	47	86
Monfore 54 (Drouin 70)	222	232
SN 76-59 59 (Drouin 70)	128	255
S1 Ice (Kjeldgaard using Drouin & Michel)	330	390
Snow Ice (Kjeldgaard using Drouin & Michel)	220	270
SN 76-66 0 m/s (Kjeldgaard)	30	60
SN 76-66 5 m/s (Kjeldgaard)	310	440
SN 76-66 20 m/s (Kjeldgaard)	410	580
Bergdahl 78		
Bergdahl 0 m/s	459	752
Bergdahl 5 m/s	502	830
Bergdahl 20 m/s	531	829

Table 3.6 Thermal Ice Forces Based on Ice Thickness

Drouin and Michel have logical derivations and laboratory tests. A thorough analysis of all data is presented by Bergdahl. On the other hand, U.S.S.R. norm SN 76-66 has tested less elaborate theories against field measurements and adjusted to conditions in nature.

No data are available for sea ice. It may be assumed that for temperature expansion is similar to fresh water ice but that there is a substantial reduction from the lower modulus of elasticity.

This assumption could be inserted in the theoretical equation presented by Bergdahl.

$$\dot{\varepsilon} = \frac{\dot{\sigma}}{E} + kD\sigma^n \qquad (3.29)$$

where:

k and n = parameters of viscous deformation, expressed as functions of strain rate and temperature
E = Young's modulus, temperature dependent
D = coefficient of self diffusion for ice molecules, temperature dependent

According to Bergdahl's formula, reductions of stresses could be substantial, perhaps in proportion to the moduli of elasticity. A reduction of the values in the table to one third seems to be permissible.

3.4.2.2 Wind Forces

Wind Shear

The general formula which expresses the shear force which wind will exert on an ice sheet has been described in the chapter on wind effects. This formula may be contracted to:

$$\tau_a = c_s w^2 \qquad (3.30)$$

where:

τ_a = wind shear
w = wind speed relative to ice
c_s = wind shear coefficient

The shear coefficient depends on the roughness of the surface. As shown in the earlier chapters, a logarithmic velocity distribution has been assumed to express the relationship.

If we adopt the expression with a compound coefficient and assume:

$\rho_a = 1.4\ \text{kg/m}^3$ (3.31)

the range becomes

$$1.3 < \frac{\tau_a}{w^2} 10^3 < 7.0 \qquad (3.32)$$

if w is in (m/sec)

and τ_a is in (Pa)

Wind Force from a Stationary Ice Sheet

A stationary wind force per unit width for an average rough cover is obtained by multiplying the above expression by the extent of the ice sheet:

$$F_w = 3.1 \times 10^{-3} \times w^2 \times a\ [\text{N/m}] \qquad (3.33)$$

where:

a = extent of ice sheet in m
w = wind speed in [m/sec]

This average steady force poses usually no danger.

Steady Wind Drag on Floes and Icebergs

Wind drag on the sail of an ice mass or ice floe have been expressed in the earlier discussion:

$$p = \rho_a C_d w^2 \qquad (3.34)$$

where:

C_d = drag coefficient
p = pressure on the sail area of ice

As an approximation we may assume $C_d = 1$ and it may be said that:

$$p = w^2 \qquad (3.35)$$

where:

C_d = a compound drag coefficient

If $\rho_a = 1.4\ \text{kg/m}^3$, the force per unit width:

$$F_d = 1.4 \times h_s \times w^2\ (\text{N/m}) \qquad (3.36)$$

where hs = sail height

where w is the average wind speed measured at 10 m above ice.

Dynamic Action

There is more danger in dynamic effects. An ice sheet is set in motion by wind, increases its speed until balanced by water shear and water drag.

Water shear may be estimated as follows:

$$\tau_f = \rho_f \left[\frac{\kappa}{\ln \frac{z + z_0}{z_0}} \; v_z \right]^2 = \rho_f c_f v_z^2 \qquad (3.37)$$

where:

τ_f = water shear
ρ_f = density of water
κ = Von Karman constant (usually 0.4)
z = depth of still water
z_0 = turbulance length of water interface
v = floe or ice sheet velocity
c_f = water shear coefficient

An approximate equation for an average rough ice cover could be written as:

$$\tau_f = \rho_w \times 4.93 \times 10^{-3} \times v_z^2 \qquad (3.38)$$

where $\rho_f = 4.93 \times 10^{-3}$

which gives in a steady drift for average rough ice:

$$\tau_a = \tau_f$$

$$v = \frac{1}{40} w \qquad (3.39)$$

if the effect of measurement based on wind speed is neglected ($w - u \approx w$).

Water Drag

For large ice masses, as icebergs, water drag becomes important:

$$p_f = \rho_f \, c_d \, v_z^2 \left[\frac{\ln \frac{h_k + z_0}{z_0}}{\ln \frac{z + z_0}{z_0}} \right]^2 = \rho_f v_z^2 \qquad (3.40)$$

where:

h_k = keel depth
c_z = retarding water drag
p_f = pressure on the keel area of ice
v_z = iceberg motion relative to the ocean

As an approximation, $C_d = 1$ is assumed

$$p_f = 1 \times \rho_f v^2 \tag{3.41}$$

and the force per unit width:

$$F_{df} = \rho_f h_k v^2 \tag{3.42}$$

For very blocky ice masses an equilibrium is reached at:

$$1.4 \times 0.15 h_k \times w^2 = 1000 h_k v^2 \tag{3.43}$$

$$v = \frac{1}{70} w \tag{3.44}$$

It is assumed:

$$w - v = w \tag{3.45}$$

3.4.2.3 Limited Drift Effect

The above expressions were obtained for no drift and for steady drift. During the acceleration phase a more complicated expression is obtained.

For an ice sheet, using notations as above the expression for drift becomes, where s is the drift length.

$$v^2 = \frac{c_s}{c_f} \frac{\rho_a}{\rho_w} w^2 [1 - \exp(-2C_s \frac{s}{h})] \tag{3.46}$$

or

$$v^2 = \frac{1}{1600} w^2 [1 - \exp(-9.86 \times 10^{-3} \frac{s}{h})] \tag{3.47}$$

which gives

$$v = \frac{1}{40} w [1 - \exp(-9.86 \times 10^{-3} \frac{s}{h})] \tag{3.48}$$

For a small drift length, the obvious result is obtained for an ice sheet:

$$v^2 = 2\,C_s \frac{\rho_a}{\rho_w} \frac{s}{h} w^2 (3.49)$$

For a linear acceleration in first phase of drift:

$$v = C_s \frac{\rho_a}{\rho_w} \frac{t}{h} w^2 = 3.1 \times 10^{-6} \frac{t}{h} w^2 \qquad (3.50)$$

Where v is terminal velocity.

or

$$\frac{v}{v_\infty} = 0.1 \left(\frac{s}{h}\right)^{\frac{1}{2}} \qquad (3.51)$$

where:

t = sec.
h = m
w and v = metres per sec.

Changing t to hours, the expression obtains the following numerical value:

$$v = 1.1 \times 10^{-2} \frac{t}{h} w^2 \qquad (3.52)$$

Croasdale (Carstens 1980 - Vol. 2, Appendix 2) gives the example that an ice floe of about 4000 m square is required to produce a static ice force of 10^7 N at winds blowing at 15 m per sec. against a structure. A supplementary statement would be that if the ice floe is stopped at 2 m penetration (which would create a load width of full diameter of 4 m in Croasdale's example) we need only a drift by about 16 m to reduce the floe to 1000 m square which would deliver the same impact. A linearly increasing force is assumed on impact. For very small drift ($s < h$), approximate formulae shown above are valid. The following expressions may be written:

Firstly, wind shear on the floe equals a static force:

$$\tau x A = F_{static}$$

In a dynamic case, drift energy equals penetration energy:

$$\tau \cdot A \cdot s = \frac{1}{2} F_{dyn} \times r \qquad (3.53)$$

$$F_{dyn} = F_{stat}\, 2 \frac{s}{z}$$

From this, the equivalent static force can be found which would give an impact force of 10^7 N:

$$F_{stat} = 6.25 \times 10^5 \text{ N} \qquad (3.54)$$

The conclusion may be drawn, that if ice floes can move even slightly in leads, contact forces are substantially increased, could be by several orders of magnitude.

3.4.2.4 Limitations of Environment Conditions

As shown in the above examples, to generate significant ice forces it is necessary to have sufficient environmental forces and transmitting agent must be a large ice sheet, which can gather momentum dynamically and the contact mass must be able to deliver the blow.

In general, the momentum of the contact mass will be exhausted as the ice floe penetrates the structure and is broken or the structure fails.

In the ice distribution section, the distribution of dangerous contact masses was given. Essentially, they are low salinity solid ice masses, icebergs, ice islands and multi-year annealed ridges and ice floes.

3.4.3 Factors Generating Ice Interaction Pressures

Table 3.7 indicates some of the key factors which will influence ice forces on a structure.

In subsequent sections, ice forces on very wide areas such as islands, narrow vertical shafts and inclined faces are discussed.

3.4.3.1 Main Load Factors

Ice effects depend on the type of ice encountered and on the geometry of structure.

Structures may be exposed to ice forces as static loading or as dynamic horizontal loads or as vertical loading from ice movement or gravity effects. Depending on the ice region and the structure, either static or dynamic effects could result in the governing design force.

There are numerous modes of ice sheet failure against a structure. The mode usually depends on the stage of the structure and the time to failure (i.e. speed of ice sheet). The most common failure types are concurrent compression by crushing and flaking, buckling and bending.

Ice forces depend on a variety of mechanical and thermal properties of ice, ice thickness, and percentage of ice cover.

State-of-the-art technology has mastered many arctic problems, but multi-year ice and icebergs are still serious obstacles.

Sea ice strength variations have been reviewed earlier. Large scale strength is in general less than test strengths, and has been proposed to be reduced by a factor for which various definitions have been proposed, which will now be discussed.

3.4.3.2 Crushing Model

It is known that environmental conditions are a predominant influence on ice forces. On the other hand, ice forces and failure modes are influenced by structural shapes. Therefore, ice force calculations are closely related to the design of the structure and vice versa. In case of an actual design it is necessary to investigate various concepts in order to select the optimum one.

The crushing mode applies for ice colliding with a vertical face. A wide contact face will flatten the colliding ice mass, ice floe or edge of an ice sheet. A narrow fall or indentor will penetrate ice.

Crushing may develop very slowly resulting in static forces. A relatively quick indentation will result in dynamic forces.

Static Forces

Static loads are considered in three loading conditions: ice frozen to structure, ice shaped to uniform contact with the interface and a rough ice edge slowly colliding with the structure.

Contact Conditions and Failure Patterns

Winter - Unfrozen - During winter, an ice sheet may approach and strike the structure. When the aspect ratio increases indefinitely, the cold hard ice will not align uniformly over the entire surface and point contacts will result with a reduced effective pressure.

Winter - Structure Frozen In - If, instead of approaching the structure from a distance and hitting it, the ice sheet is frozen in around the structure when it begins to move the forces encountered could be greater. When ice freezes around objects in tidal conditions, it often forms a bustle or thickening which forces failure to occur at some distance from the interface. If this happens a simultaneous failure of the ice edge forms with full unconfined compression developed over the full face. Since the ice is hard and brittle this condition would probably only last momentarily after which full unconfined compression would develop over 0.6 of the contact face. As the aspect ratio increased indefinitely, the statistical average would again prevail.

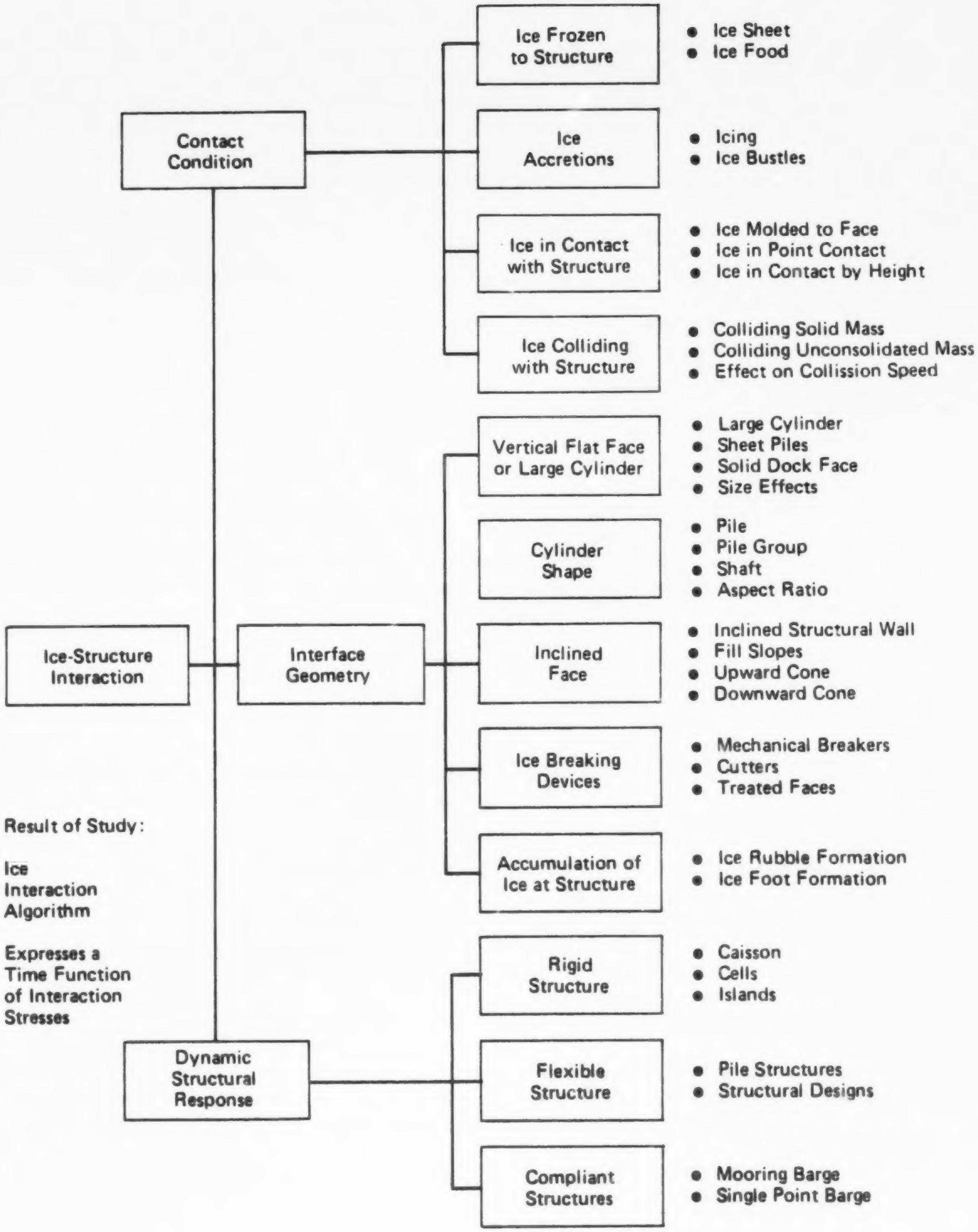

Ice-Structure Interaction
Contact Condition
Ice Frozen to Structure
• Ice Sheet
• Ice Food
Ice Accretions
• Icing
• Ice Bustles
Ice in Contact with Structure
• Ice Molded to Face
• Ice in Point Contact
• Ice in Contact by Height
Ice Colliding with Structure
• Colliding Solid Mass
• Colliding Unconsolidated Mass
• Effect on Collission Speed
Interface Geometry
Vertical Flat Face or Large Cylinder
• Large Cylinder
• Sheet Piles
• Solid Dock Face
• Size Effects
Cylinder Shape
• Pile
• Pile Group
• Shaft
• Aspect Ratio
Inclined Face
• Inclined Structural Wall
• Fill Slopes
• Upward Cone
• Downward Cone
Ice Breaking Devices
• Mechanical Breakers
• Cutters
• Treated Faces
Accumulation of Ice at Structure
• Ice Rubble Formation
• Ice Foot Formation
Dynamic Structural Response
Rigid Structure
• Caisson
• Cells
• Islands
Flexible Structure
• Pile Structures
• Structural Designs
Compliant Structures
• Mooring Barge
• Single Point Barge
Result of Study:
Ice Interaction Algorithm
Expresses a Time Function of Interaction Stresses

Table 3.7 Factors Generating Ice Interaction Pressures

Spring - Warm Moldable Ice - The same basic failure mechanisms apply for this type of the ice until D/h exceeds 1. At this time full contact can occur over the whole face and, because of the moldability of this ice, full contact can remain in effect for quite large D/h values and for a larger period of time. Eventually the statistical average must again prevail.

Review of Suggested Ice Loads

All design practices accept the concept of "Effective Pressure" p_e given by:

$$p_e = P/bh \qquad (3.55)$$

where:

p_e = ice force
b = width of pile or pier
h = ice sheet thickness

In addition to basic ice strength p_e depends on many other factors. All the design practices consider these factors in some way or other.

The review of existing design practices follows tabulations by IAHR as collected by Croasdale (Carstens 1980 - Vol. 2, Appendix 2). Tabulations will be supplemented by additional derivations.

In putting forward these guidelines, we have taken into account the following considerations:

1. nature of ice thrust static or dynamic;
2. mechanism of ice thrust and failure process;
3. aspect ratio;
4. characteristic peaks during dynamic action
5. moving ice pack with unconsolidated individual floes;
6. unconsolidated and consolidated pressure ridges;
7. ice cutting process;
8. energy concept (energy required to break the ice).

The problem with perfect contact is solved by Croasdale using plasticity theory. Coulomb-Prandtl results adding the effects of internal frictions and analyses by brittle-elastic assumptions are added below.

Plasticity Theory

For perfect contact the problem reduces to that of pushing an indentor into the edge of a semi-infinite ice sheet.

Various yield criteria have been used by Ralston to analyse the stress in ice as an isotropic, homogeneous ideal elastic-plastic material. Yielding is governed by a relation between the principal stresses known as the yield criterion.

Plasticity theory based on Tresca yield criterion gives:

$$\frac{p_e}{\sigma_u} = \frac{\pi}{2} \qquad (3.56)$$

for a very narrow indenter and:

$$\frac{p_e}{\sigma_u} = 1 \qquad (3.57)$$

for a very wide indenter.

Simplified Wedge Theory

Assuming symmetrical double wedges for initial geotechnically modelled failure, the initial conditions can be expressed by the following formula:

$$\frac{p_e}{\sigma_u} = (1 + 0.304 \frac{t}{b}) K \qquad (3.58)$$

Croasdale adds a further reduction by Korzhavin type contour factor suggested k = 0.5. A similar presentation has been made by Tryde (1977 - Vol. 2, Appendix 2) to yield the formula:

$$\frac{p_e}{\sigma_u} = 0.8 + 1.68 \left(0.4 + \frac{d}{t}\right)^{-1} \qquad (3.59)$$

Theory of Michel and Toussaint

For a very narrow indenter, the theory of Michel and Toussaint has promise. It is based on a plastic zone development under the load.

It is proposed to use three separate equations for ice pressure, each for a specific strain rate range, they are:

(a) For $10^{-8}\ s^{-1} < \dot{\varepsilon} < 5 \times 10^{-4}\ s^{-1}$ (ductile zone)

$$p = 2.97\ m\ k\sigma_0 \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{-0.32} \qquad (3.60)$$

where m = 1 for a flat indentor 1.0 for initial good contact, k = 0.6 for continuous crushing, σ_0 = 7000 kPa for ice at -10°C,

$\dot{\varepsilon}_0 = 5 \times 10^{-4}\ s^{-1}$

(b) For $5 \times 10^{-4}\ s^{-1} < \dot{\varepsilon} < 10^{-2}\ s^{-1}$ (transition zone)

$$p = 2.97\ m\ k\sigma_0 \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{-0.126} \qquad (3.61)$$

where k = 0.25 for continuous crushing and the other parameter have values as in (a).

(c) For $\dot{\varepsilon} > 10^{-2}\ s^{-1}$ (brittle zone)

$$p = 3\ mk\ \sigma_b \qquad (3.62)$$

where k = 0.3 for continuous crushing and σ_b is the uniaxial crushing strength under brittle conditions.

Static Peak Loads for Material with Internal Friction

Static initial forces are discussed below, caused by moving ice or stresses which develop within the ice.

Basic Concepts - If a thick ice sheet impinges on a pile with a small diameter, the aspect ratio is considered to be small. Essentially if this structure is to withstand the force of a large moving ice sheet, it must cut a path through the ice. For such a narrow structure, the load stress situation is analogous to that of a long, thin foundation bearing on a semi-infinite medium. The ultimate pressure developed under a strip load on a semi-infinite medium is denoted as p_s. According to Reinicke (1979 - Vol. 2, Appendix 2) the shape of the structure (round or flat) has little effect on the magnitude of p_s. If the material is ductile, plastic flow occurs when the shear stress reaches its shear strength.

The strip load pressure (p_s) is a multiple of the unconfined compressive strength and the ratio between pressure and strength is termed identation factor in ice mechanics. The factor depends on the strain rate and the type of ice. Based on calculations carried out by Reinicke (1979 - Vol. 2, Appendix 2) a factor of 3 and 1.2 was found for columnar and granular ice, respectively. Field tests indicated a value of 2.2 which can be considered as an average value.

A further variable which has a considerable bearing on the effective ice strength in case of a thin pile is the magnitude of the wedge angle. As mentioned above, if stresses at the structure edge reach the strength of the ice, material is pushed around leaving an intact trunkated edge of ice as shown in Figure 3.2. A Prandtl type failure mechanism can be assumed and the indentation factor can be expressed as:

$$\frac{p_s}{\sigma_c} = \frac{1}{2 \sin \phi} (1 + \sin \phi)\, e^{2\Theta \tan \phi} - 1 + \sin \phi) \qquad (3.63)$$

For an ideally plastic substance, i.e., $\phi = 0$, the above equation reduces to:

$$\frac{p_s}{\sigma_0} = 1 + \Theta \qquad (3.64)$$

where Θ = wedge angle. In case of a perfectly flat structure - ice interface $\Theta = \pi/2$ and the effective pressure reaches its classical value of $p_s = 2.5708$. This is a maximum value for $\phi = 0$ but a minimum value for ice since the internal friction angle has been neglected. Angles of 15 to 20° have been quoted by Assur (1972 - Vol. 2, Appendix 2). Wedge angles of 45 to 50° were suggested by Popov et al. (1968 - Vol. 2, Appendix 2). For $\phi = 45°$ and $\phi = 15°$-$20°$, $p_s = 2.3\ \sigma_c - 2.5\ \sigma_c$.

As the aspect ratio increases to about one, the failure mechanisms gradually changes. The pure Prandtl type failure does not occur any more because in addition to material being pushed around the side, the structure begins to flake ice in the vertical direction in an unconfined compression type failure. Thus the effective pressure on the structure is now a combination of the confined and unconfined compressive strengths of ice. As D/h increases to large values, the effects of pushing material sideways around the structure becomes negligible and vertical flaking predominates. This vertical flaking occurs at stresses which are equal to the unconfined compressive strength of the ice. Field measurements have shown that the effective pressure on very wide structures is much less than the unconfined compressive strength of ice as determined from small scale tests. This phenomenon is accounted for by the fact that statistically, full, uniform contact does not occur over the width of the structure but only does so at certain selected points while elsewhere the pressure is some fraction of the average.

During the spring, as the ice warms up to the melting point it loses some of its strength but it becomes very moldable. Thus, warm ice with its low strength but considerable larger contact area could develop a higher force than the stronger cold ice.

Brittle-Elastic Theory

By applying the brittle-elastic theory for the failure of cold ice, lower effective pressures would be obtained for low internal friction. Higher internal friction gives results which are comparable to the plasticity theory. Following results are for a narrow pier where the material flows sideways (Kivisild and Iyer 1976 - Vol. 2, Page 15).

$$\text{If } \rho = 0, \quad \frac{Pe}{\sigma_n} = 1.57 \qquad (3.65)$$

$$\text{If } \rho = 45^\circ, \quad \frac{Pe}{\sigma_n} = 2.99 \qquad (3.66)$$

Comparison of Results

From Croasdale (Carstens 1980 - Vol. 2, Appendix 2) the ice pressures calculated using the wedge theory are calculated on the basis of a contact factor of 0.5. Also it is assumed that a shape factor $m = 0.9$. For the narrow structure, $b = 3$ m and $t = 1$ m. For the wide structure $b = 30$ m and $t = 1$ m. The equation then reduces to the following quoted expression:

$$p = 0.59\ \sigma_c \text{ for the narrow structure} \qquad (3.67)$$

and

$$p = 0.46\ \sigma_c \text{ for the wider structure} \qquad (3.68)$$

σ_c is taken to be 7000 kPa for ice at -10°C and 3000 kPa for ice at -1.5°C.

Similar assumptions for ice strength and structure width were made in using the equations of Michel and Toussaint. It was assumed that the ductile ice pressure occurred at the maximum ice strength value. Contact factors were 0.6 for the ductile condition and 0.3 for the brittle condition.

In looking at the values listed in Table 3.8, several points can be noted.

- The values given by existing guidelines are lower than the highest values given by the formulae.

- The guidelines do not relate specifically to ice temperature or to structure width. It is likely that the design guidelines relate to warm ice as might be experienced at break-up.

Quoting Carsten again, even in the Arctic the mean ice temperature is unlikely to get much below -10°C because of the insulating effect of the snow cover. Furthermore, the values calculated are based on fresh ice; sea ice is weaker and so the ice pressures in crushing would be lower.

Croasdale recommends to use the wedge formula with k = 0.5. It is recommended that it be used for design where conditions may be different from those of the guidelines, e.g. in the arctic. The wedge fromula has the advantage of accounting for structure width, thickness, and ice strength. For ice in more or less continuous motion a value of contact factor of 0.5 is suggested. If ice can freeze around a structure, then a value of k = 1.0 or higher may be appropriate. It would seem wise to prevent good contact from occurring by the deployment of waste heat or use of other defence measures.

For very wide structures a further mitigation of ice forces may occur due to non-simultaneous failure across the width of the structure.

Continuous Crushing of a Wide Structure

Failure of an Ice Sheet at a Wide Vertical Structure - The breakdown of an ice sheet driven against a wide vertical structure ($D/h > 5$) by environmental forces such as wind or current can be explained by a sequence of events. Because of its rugged surface, failure of the ice sheet edge does not take place simultaneously along its entire length but only at a few places along its edge.

Upon contact with the structure upward or downward flaking of the sheet takes place. Forward movement of the sheet results in flattening of the pointed edge which was created during flaking. As shown in Figure 3.32, flaking and flattening alternate. The speed at which this alternating process takes place depends on the velocity of the approaching ice sheet.

Flaking - The flaking mechanism has been discussed earlier. As shown in Figure 3.32, the volume of the flake depends on the internal friction angle ϕ of the ice. The work done during flaking is the integral of the flaking force over its associated dis-

Source		Range of Pressures Specified or Implied (kPa)
Korzhavin 1962: USSR Rivers, Spring Break-Up		490-1860
AASHO and CSA (Old): Highway Bridge Codes		2760
New CSA Code S-6 (1974): Highway Bridges		690-2760
USSR Code SN 76-66: River Structures		295-1320
Canada Ministry of Transport: Navigation Lightpiers, St. Lawrence		965-1210
Canada Department of Public Works: Wharf Piles		1380-1720
Wedge Formula	3 m dia. Structure	1755
(Warm Ice -1.5°C)	30 m dia. Structure	1390
Michel and Toussaint	Ductile	4811
(Warm Ice -1.5°C)	Brittle	1620
Tryde (-1.5°C)	3 m dia. Structure	3860
	30 m dia. Structure	2580
Wedge Formula	3 m dia. Structure	4095
(Cold Ice -10°C)	30 m dia. Structure	3244
Michel and Toussaint	Ductile	11226
(Cold Ice -10°C)	Brittle	4050
Tryde (-10°C)	3 m dia. Structure	9070
	30 m dia. Structure	5990
Fenco Wedge Theory	3 m dia. Structure	4900
(Cold Ice -10°C)	30 m dia. Structure	3400

Table 3.8 Comparison of Effective Pressures for Vertical Piles and Piers

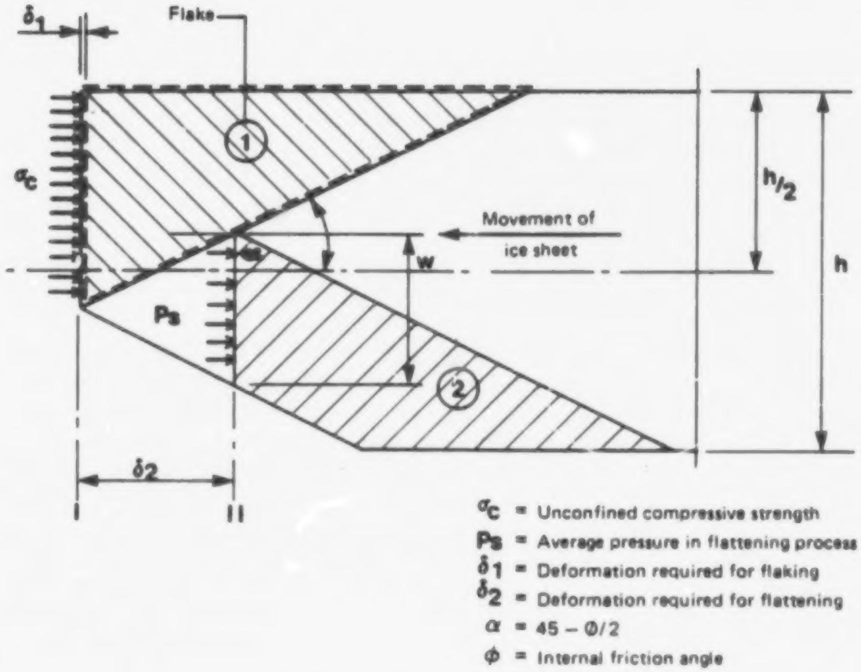

δ_1
Flake
1
2
σ_c
P_s
$h/2$
h
w
Movement of ice sheet
δ_2
I
II
σ_c = Unconfined compressive strength
P_s = Average pressure in flattening process
δ_1 = Deformation required for flaking
δ_2 = Deformation required for flattening
α = 45 – Ø/2
ϕ = Internal friction angle

Figure 3.32 Sequential Breakdown of Edge of Ice Sheet

placement δ (Figure 3.32). The peak flaking force had been derived to yield 0.9 $h^2\ \sigma_c$. The specific energy SE which is required to break a unit volume can be related for steady collision speed to time average breaking pressure. This relationship may be given by:

$$SE\ (\frac{kJ}{m^3}) = \frac{A\int \sigma_c d\ \delta\ (kPa)}{V} \qquad (3.69)$$

where:

SE = specific energy, either in $(\frac{kJ}{m^3})$ or (kPa) since 1 $(\frac{kJ}{m^3})$ = 1 (KPa)

V = volume of material flaked (m^3)
δ = displacement (m)
A = flaking area (m^2)
σ_c = flaking strength (kPa)

Based on test results the specific energy (flaking energy) for the break-out of a piece from an edge of an ice sheet of cold area ice is 500 kPa. The maximum unconfined compression strength σ_c = 8000 kPa. For α (Figure 3.32) a value of approximately 26° is assumed. Assuming the break-out to happen at a constant stress, an approximate mathematical relationship may be written for flaking energy and deformation.

$$\delta \approx \frac{h \cdot SE \cdot a}{\sigma_c} \qquad \alpha = 26° \; a = \frac{4}{7} \tag{3.70}$$

Therefore:

$$\delta_1 = 0.036\ h \text{ or } \frac{\delta_1}{h} = 0.036 \tag{3.71}$$

It can be seen that the deformation required to initiate flaking depends on the energy ratio SE/σ_c which in turn depends on the type of ice and the type of loading.

Flattening - Flattening of the edge takes place by successive failures of a truncated wedge when the colliding ice mass moves from Section I to Section II (see Figure 3.32). At Section II stresses at the edge would reach a value which would develop in a strip type loading. Assuming a ratio $ps/\sigma_c = 2$, the width of

the strip $w = \frac{2h}{7}$ and the length of the strip $s = 1.58\ h$.

The distance between two flakes can easily be found from the geometry as:

$$\delta_2 = \left(\frac{w}{2}\right)/\tan\alpha \tag{3.72}$$

with $\tan\alpha = 0.5$

$$\delta_2 = w = \frac{2}{7} h \tag{3.73}$$

Energy Relationships - In the model shown in Figure 3.32 it is assumed that the same energy is required to cause failure of flake (1) and flake (2). The total failure energy for each flake consists of a flaking energy component and a flattening energy component. From geometry it was found that the flaking energy and flattening energy multiplied by their associated volumes amounted to $16/49\ h^2\ \sigma_{cf}$ and $2/49\ h^2\ \sigma_{ef}$, respectively. The values of σ_{cf} and σ_{ef} have been listed in Table 2.1 for three types of ice. The crumbling volume amounts of $\delta_2 h = 2/7\ h^2$.

$$SE = \frac{\frac{16}{49} h^2 \sigma_{cf} + \frac{2}{49} h^2 \sigma_{ef}}{\frac{2}{7} h^2} \tag{3.74}$$

$SE = 714$ kPa

The value for the crumbling energy of 714 kPa compares reasonably well with observed 750 kPa. It appears reasonable to assume that the process of flattening is closely related to that of a confined compressive failure mechanism. The energy developed during the flattening depends to a large extent on the pressure p_s which in turn depends on the wedge angle, the angle of internal friction and the unconfined compressive strength σ_c.

The force-deformation relationship for one failure cycle is illustrated in Figure 3.33.

From the model given in Figure 3.32 and the graph in Figure 3.33, it can be seen that some flattening takes place already during the flaking process.

For cold sea ice the foregoing calculations have shown that the flaking energy amounts to about four times the flattening energy. As shown in Figure 3.33, the deformation causing flaking is about 6% of the flattening deformation.

If one assumes that an ice sheet travels at a constant speed against a wide vertical structure it can easily be visualized that the time to initiate flaking is considerably less than time required to complete flattening of the edge.

Instantaneous Loading Probability for Moving Ice Sheet

The flaking-flattening model derived in the previous section applies only to one single channel interacting with a vertical structure face. The definition of a channel is shown below.

The discussion shown below is based on channels with a width equal to largest individual flakes. Kry (1978 - Vol. 2, Page 106) presented a similar discussion based on channels with a width of 4 h. Results from Kry's work are comparable.

The designer of a wide structure subjected to the action of ice is interested in the average pressure of the impinging ice sheet. Based on probabilistic methods, relationships have been developed for cold sea ice which relate instantaneous pressure to the width of structure (or number of channels) by assuming various exceedance probabilities.

Procedure

Let the number of channels:

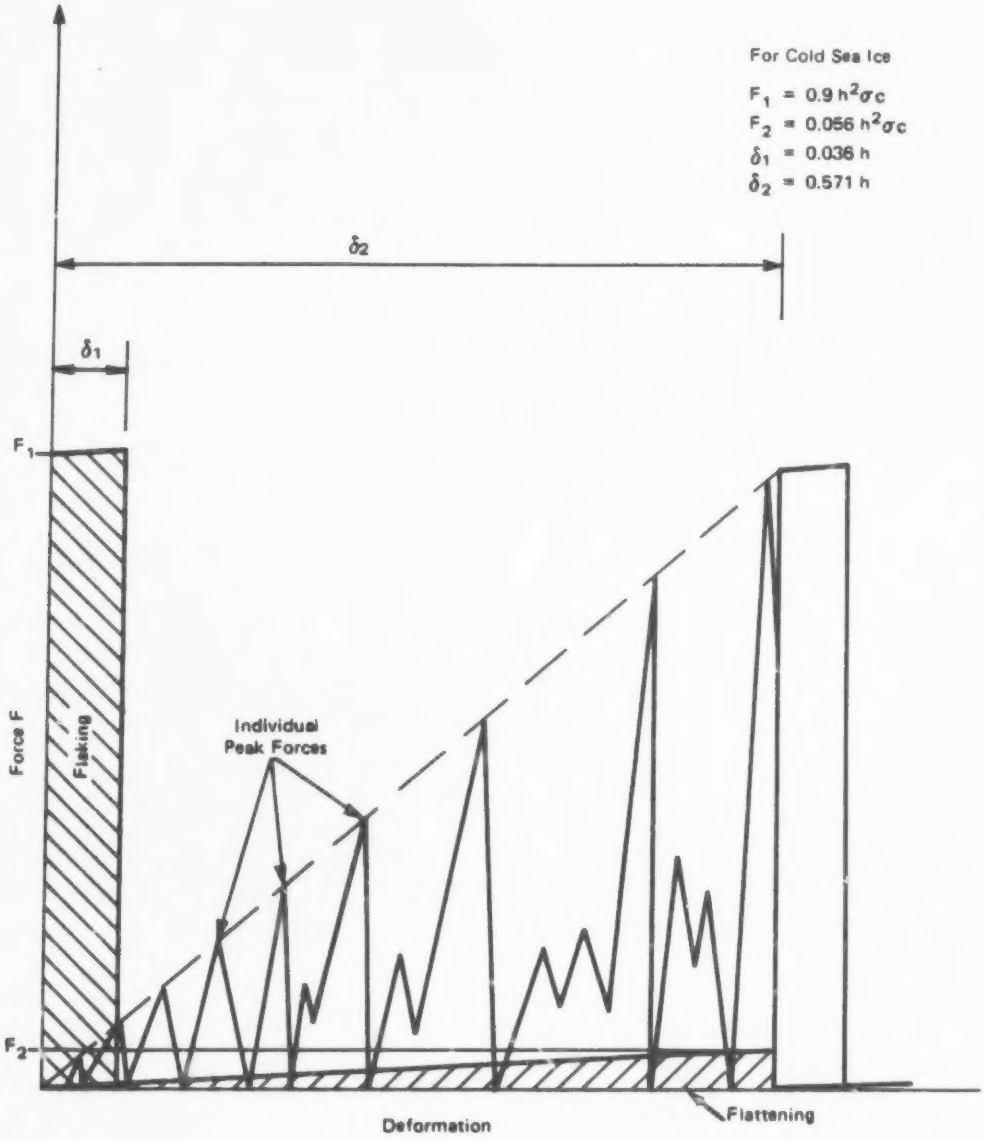
$$n = \frac{D}{hk_1} \qquad (3.75)$$

where k_1 is a parameter, typically around 1.6, and is a function of the internal friction angle.

For a single channel, define the probability distribution of pressure F as:

$$P(F_o) = P\ (t{:}\ F(t) \leq F_o) \tag{3.76}$$

where t is time. The probability for the ice flaking model is shown in Figure 3.34. The probability density is then:



For Cold Sea Ice
$F_1 = 0.9\,h^2\sigma c$
$F_2 = 0.056\,h^2\sigma c$
$\delta_1 = 0.036\,h$
$\delta_2 = 0.571\,h$
δ_2
δ_1
F_1
F_2
Force F
Flaking
Individual Peak Forces
Deformation
Flattening

Figure 3.33 Force – Deformation Diagram

$$p(F_o) = \frac{d}{dF} P(F_o) \qquad (3.77)$$

and is shown in Figure 3.35.

The ice channels are assumed to be stochastically independent. The joint probability density for n channels, each with a density p(F) is:

$$p_n\ (F) = n\ (p(nF)^{*n}) \qquad (3.78)$$

where $*n$ represents convolution across n functions.

The central limit theorem of probability requires that each component peak of the probability density approach a Gaussian form with increased n. Eventually peak overlap results in an acceptable joint density function being given by:

$$p_n(F) = (1 + \frac{F_o}{2F_1}) \cdot \frac{\Gamma(n+1)}{\Gamma[(F)+1]\Gamma[n+1-k(F)]} \cdot (\frac{\delta_1}{\delta_2})^{k(F)} \cdot (1 - \frac{\sigma_1}{\sigma_2})^{n-k(F)} \qquad (3.79)$$

where $n = \frac{d}{hk_1}$ and:

$$k(F) = nF\ (1 + \frac{F_o}{2F_1}) - \frac{nF_0}{2F_1} \qquad (3.80)$$

Based on this equation, pressure density functions for three different n's are plotted in Figure 3.36. Exceedance factors of 10%, 1% and 0.1% over expected pressures are plotted in Figure 3.37.

It should be noted that the curves shown in Figure 3.37 have been derived for cold sea water ice. Similar curves can be determined for other types of ice. Furthermore, it should be kept in mind that the foregoing probability calculations are based on the model developed above, i.e. up or downwards flaking is assumed. Obviously, this model becomes erroneous as n approaches zero. As mentioned previously, for small aspect ratios (< 0.4) a Prandtl type failure can be assumed.

The time aspect of the flaking-flattening process will be discussed in the following section.

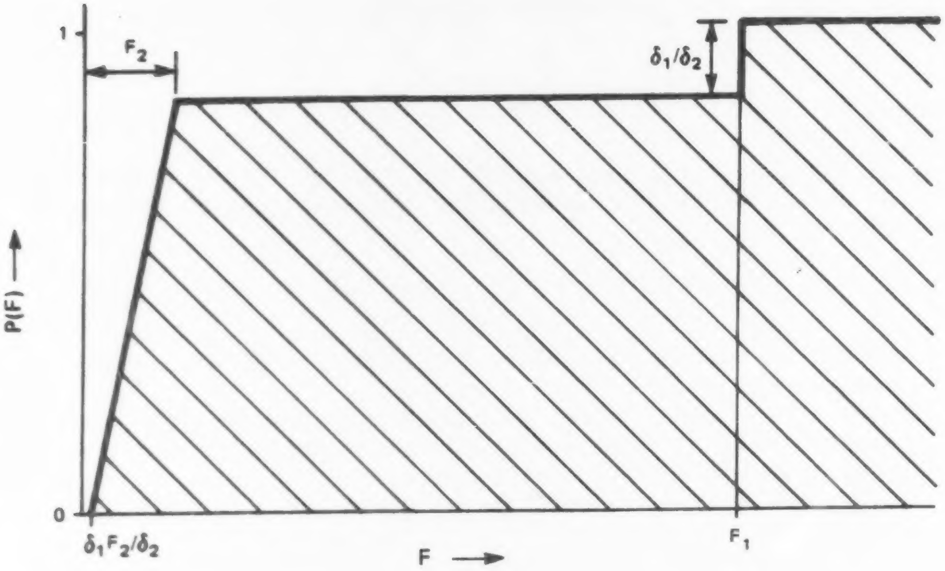


Figure 3.34 Probability Distribution

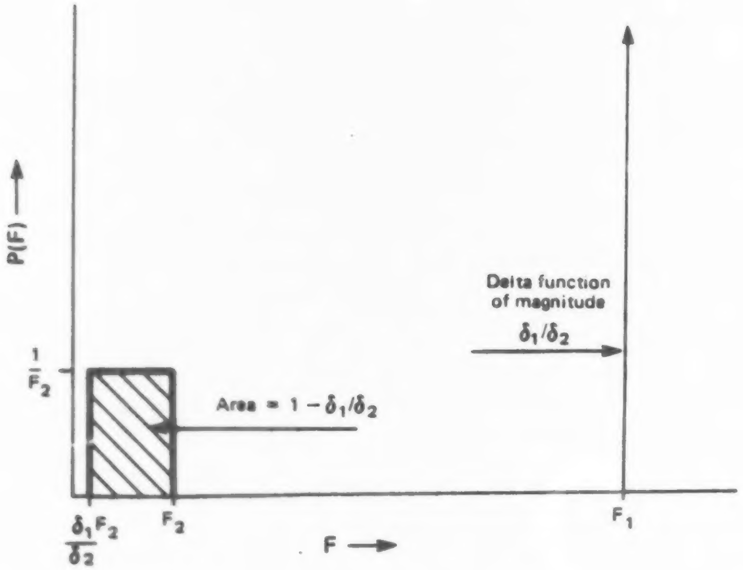


Figure 3.35 Probability Density for One Channel

High Velocity Impacts - Inside Ice Cover

During elastic impact of ice floe and the structure, the leading edge of the floe will recede relative to the body of the floe. At the moment of impact, the body of the floe moves at the collision velocity v. At these moments, the stressed cross-section is the same as the contact area. There is a zone inside the cover where ice is compressed at a stress equal to the average contact pressure.

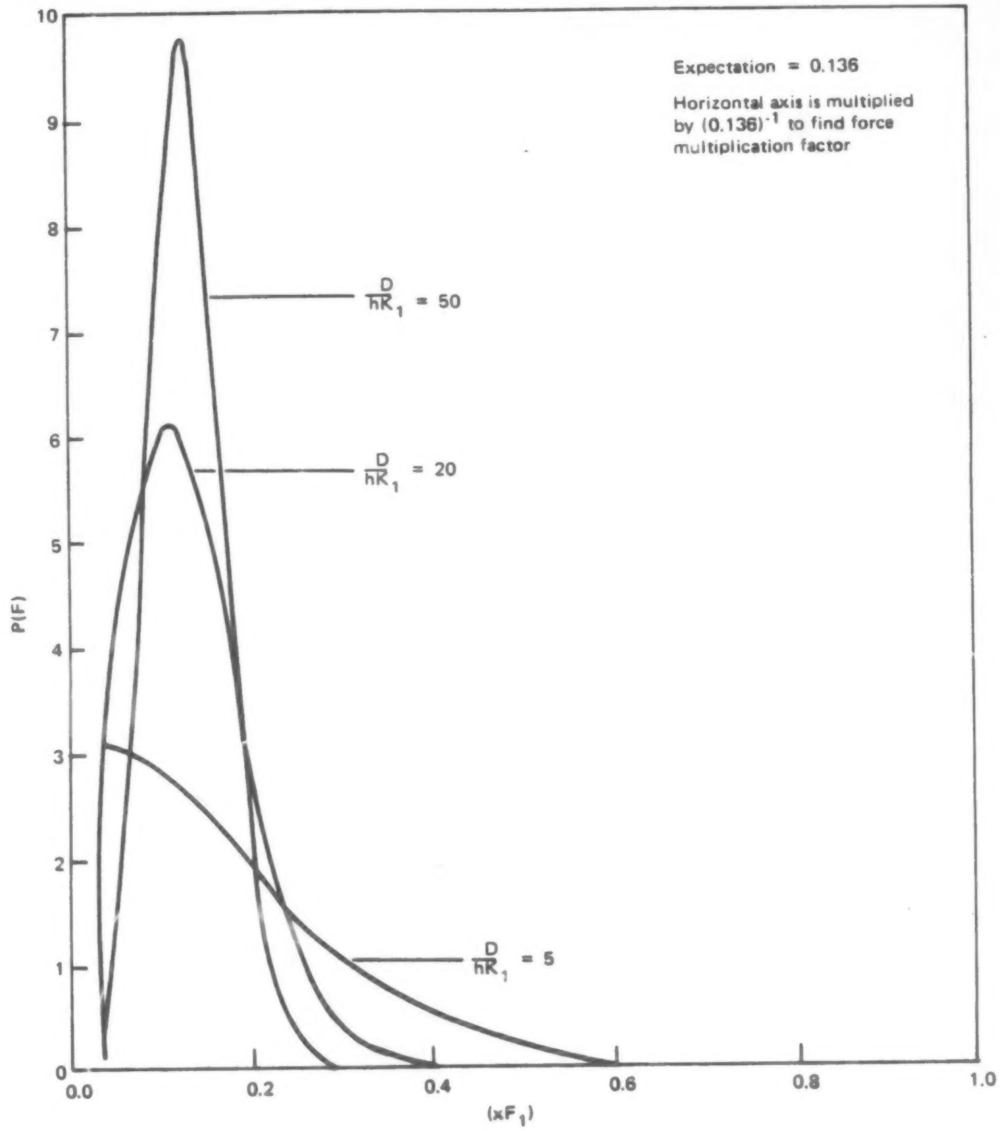


Figure 3.36 Probability Density of Instantaneous Pressure

i) Dynamic limit pressure - solid ice sheet.

The initial contact pressure due to collision is given by:

$$p = 0.105 \frac{(E\rho_w)^{\frac{1}{2}}}{g} v \qquad (3.81)$$

The tabulated values for the limiting pressure are obtained by substituting the values in this expression.

At a critical velocity v_{cr}, $p_{max} = 3150\ v_{cr}$ if v is in m/sec p is in kPa reaches failure loads (velocity at which structure starts penetrating continuously) brittle failure of ice results.

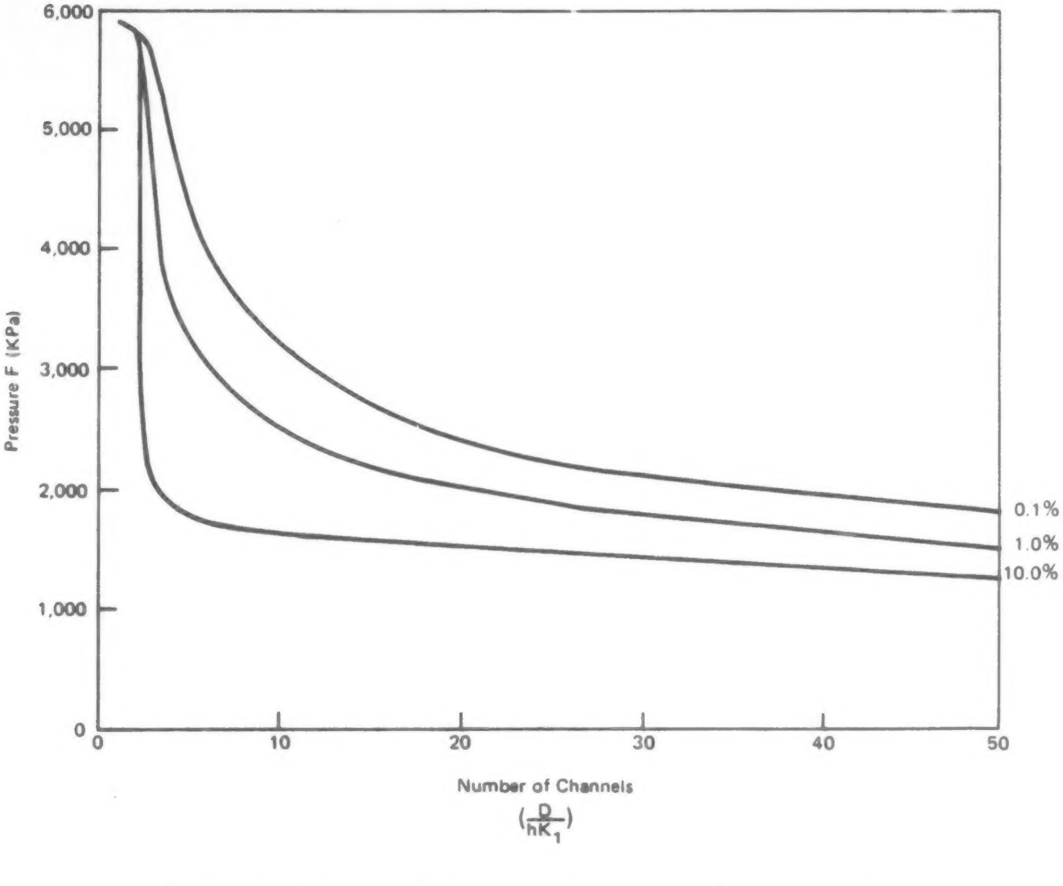


Figure 3.37 Exceedance Probabilities of Instantaneous Pressure for Cold Sea Ice

ii) Dynamic limit in uniform pack.

Only limited contact is produced in a pack, which causes a sharp reduction to the modulus of plasticity.

Assuming the values of virtual modulus in the expression for dynamic limit pressure, the value for the pack is obtained as:

$$p = 3150\ v\ (1/16)^{1/2} = 750\ v\ \text{kPa} \qquad (3.82)$$

where v is in m/sec, for fresh water ice.

Values are similarly obtained for sea ice.

High Velocity Impacts - At Edge of Ice

i) Average energy during incision into compact ice.

As mentioned before, if the floe moves at a velocity higher than a certain critical velocity v_{cr}, the pressure would exceed the compressive strength temporarily. The structure will incise into the sheet continuously and will break in brittle failure. The time average pressure at the edge during the continuous breaking process results in an average value which is about 1/2 p_{cr}.

ii) Maximum pressure during impact which dislodges part of compact pack.

The failure mechanism for a loose pack is assumed as due to dislodgement of the floes by rotation in the pack around the structure as in Figure 3.3.8. A circular fracture plane is assumed. Theoretical investigation leads to the tabulated results for the pressure p (Figure 3.3.8).

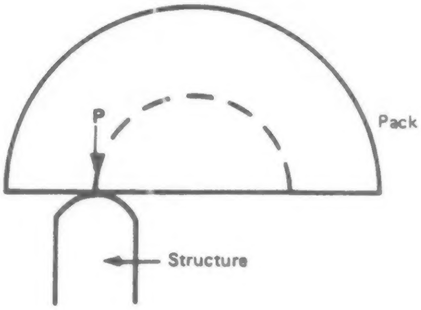


Figure 3.38 Definition Sketch

iii) Loose pack with free flow values.

In the case of a loose pack freely floating, the pressure is due to hydrodynamic effects due to the velocity of water and is given by:

$$p = 1/2\ C_d\ \rho v^2 \qquad (3.83)$$

The coefficient of drag which depends on the Reynolds number taking C_d as 2 and ρ as 1000 kg/m^3, we get $p = v^2$(kPa) where v is in m/sec.

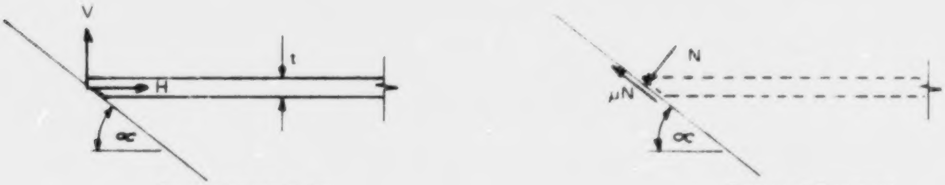
Uniform Ice Acting on a Sloping Structure

This item is discussed according to Croasdale as presented in IAHR Guidelines (Carstens 1980). Therefore, only a summary is presented.

Interaction Mechanism

Consider the simplified two-dimensional system shown in Figure 3.39. As the advancing ice sheet first encounters the sloping structure, local crushing occurs on the underside of the ice sheet. The local crushing causes an interaction force normal to the structure surface. In addition, because the ice is moving relative to the surface, a frictional force is also generated.

The normal and tangential forces can be resolved into vertical and horizontal components V and H acting at the centre of the crushed area. In the simple two-dimensional model (Figure 3.39), the forces acting on the ice will be V, H, gravity and buoyancy forces; the latter can be considered as an elastic foundation.



Forces Acting on Ice

Forces on Structure

Figure 3.39 Initial Interaction Between Ice and Sloping Structure

As the ice sheet continues to advance the crushed area will increase causing V and H to increase. Assuming an unlimited driving force, V and H will continue to increase until the ice fails. For a properly designed sloping structure the ice should fail in bending.

Simple Theory - Two-Dimensions

To gain an appreciation of the influence of various parameters it will be useful to consider a two-dimensional system and derive some simple equations.

Consider the initial interaction between ice and the sloping face. The relationships between V, H, N and α can be derived by resolving forces, that is:

$$H = N \sin\alpha + \mu N \cos\alpha$$

$$V = N \cos\alpha - \mu N \sin\alpha$$

therefore:

$$H = V \left(\frac{\sin\alpha + \mu\cos\alpha}{\cos\alpha - \mu\sin\alpha}\right) \qquad (3.84)$$

In the limit, the maximum value of V will be limited by its bending moment capacity Mo.

$$\sigma_f = \frac{6Mo}{bt^2} \qquad (3.85)$$

Where b is the width of the beam and t is the ice thickness.

The initial horizontal force on the structure per unit width is given by:

$$H/b = 0.68\ \sigma_f \left(\frac{\rho_w g t}{E}\right)^{\frac{1}{4}} \frac{\sin\alpha + \mu\cos\alpha}{\cos\alpha - \mu\sin\alpha} \qquad (3.86)$$

The above can be thought of as the component required to break the advancing ice. For subsequent interactions a component is also required to push the ice up the slope. The force system in this latter case is shown in Figure 3.40. P is the force required to push the ice up the slope, then:

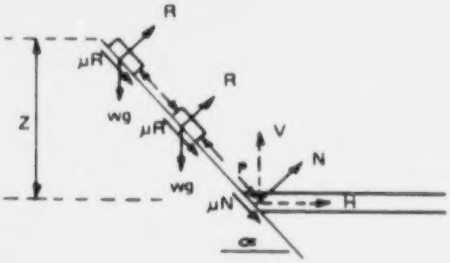


Figure 3.40 General Interaction Between Ice and Sloping Structure

$$P = \frac{Z}{\sin\alpha}\, t b \rho_i g\, (\sin\alpha + \mu\cos\alpha) \qquad (3.87)$$

Where Z is the height reached by the ice on the slope, and ρi is the density of the ice, then:

$$H = (V + P \sin\sigma)\left(\frac{\sin\sigma + \mu\cos\alpha}{\cos\alpha - \mu\sin\alpha}\right) + P \cos\alpha \qquad (3.88)$$

substituting for V and P gives:

$$\frac{H}{b} = 0.68\, \sigma_f \left(\frac{\rho_w g t}{E}\right)^{\frac{1}{4}} t \left(\frac{\sin\alpha + \mu\cos\alpha}{\cos\alpha - \mu\sin\alpha}\right) + Z t \rho_i g \left(\frac{(\sin\alpha + \mu\cos\alpha)^2}{\cos\alpha - \mu\sin\alpha} + \frac{\sin\alpha + \mu\cos\alpha}{\tan\alpha}\right) \qquad (3.89)$$

Total force is given by the equation:

$$\frac{H}{b} = \sigma_f \left(\frac{\rho_w g t}{E}\right)^{\frac{1}{4}} C_1 + Z t \rho_i g\, C_2 \qquad (3.90)$$

where C_1 and C_2 are functions only of α and μ. Values for the coefficients C_1 and C_1 are plotted in Figures 3.41 and 3.42 for typical values of α and μ.

Effect of Friction and Slope Angle

For a typical example of a structure with a freeboard of 5 m subject to forces imposed by ice 1 m thick with a flexural strength of 700 kPa, the effect of friction and slope angle is shown in Figure 3.43. For steep angles and high friction the ice may fail in crushing rather than bending.

Effect of Ice Strength

The ice strength affects the ice breaking component but not the ride-up component. As shown in Figure 3.44, in this simple 2-D elastic analysis, the ride-up force in a typical example is larger than the breaking force, so the effect of ice strength on total force is not as significant on large structures as one might suppose.

Effect of Ice Thickness

Ice thickness is probably the most significant parameter affecting ice forces on sloping structures. In the simple 2-D analysis, the ice breaking component is proportional to $(t)^{1.25}$ and the ride-up force is directly proportional to t. The effect of thickness for a typical example is shown in Figure 3.45.

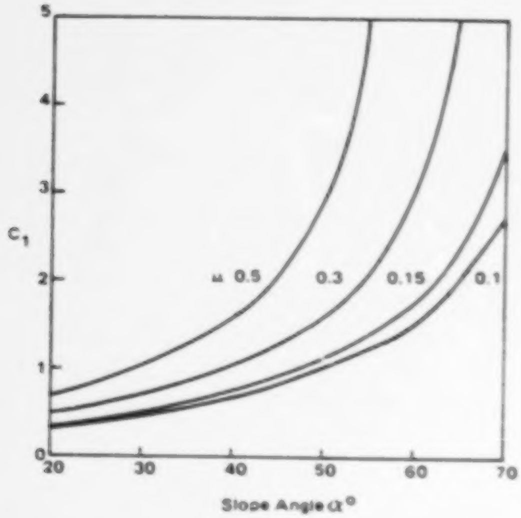


Figure 3.41 C_1 vs Slope Angle and Friction

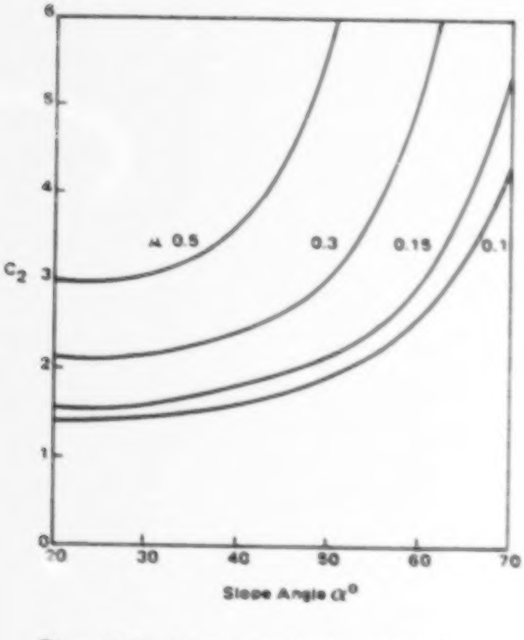


Figure 3.42 C_2 vs Slope Angle and Friction

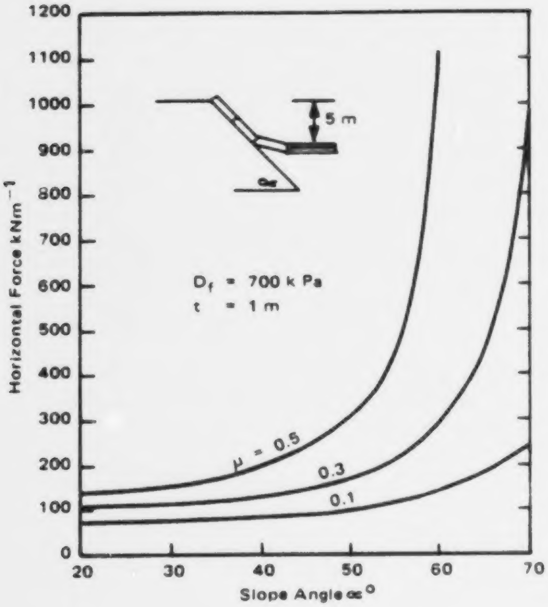


Figure 3.43 Horizontal Force vs Slope Angle and Friction (Simple 2-D Theory)

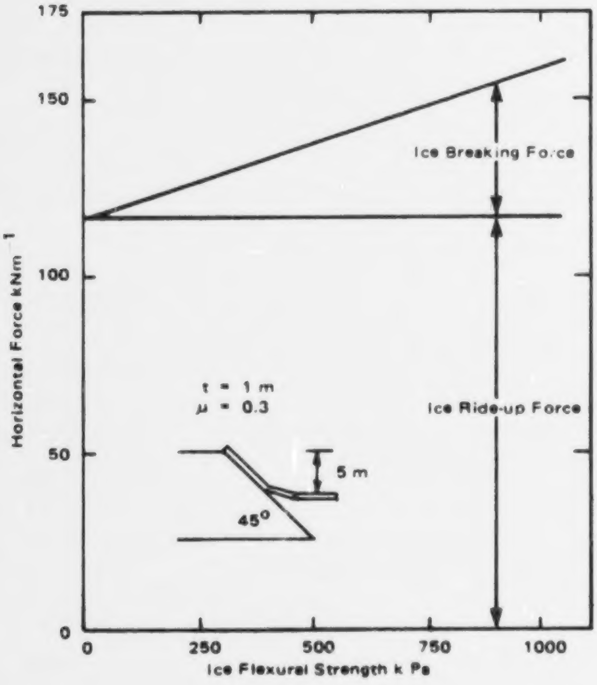


Figure 3.44 Effect of Ice Strength on Horizontal Force (Simple 2-D Theory)

Three Dimensional Theory

For the ice breaking component, the simple beam theory is replaced by a more complex plate theory for which elastic analyses have been made using theories developed for plates on elastic supports. Nevel (1972) has proposed equations for the ultimate failure of ice plates which can be applied to this problem.

It is generally assumed that the essence of the ice force problem on a conical structure reduces to the prediction of the forces necessary to fail a series of ice wedges formed by radial cracking of the ice as it advances against the cone, see Figure 3.46.

Nevel's (1972 - Vol. 2, Appendix 2) equation for the force to fail these wedges is given as:

$$\frac{6P}{b\,\sigma t^2} = 1.95 + 2.00\,(a/\ell) + 0.50\,(a/\ell)^3 \qquad (3.91)$$

where ℓ = elastic radius of the ice sheet.

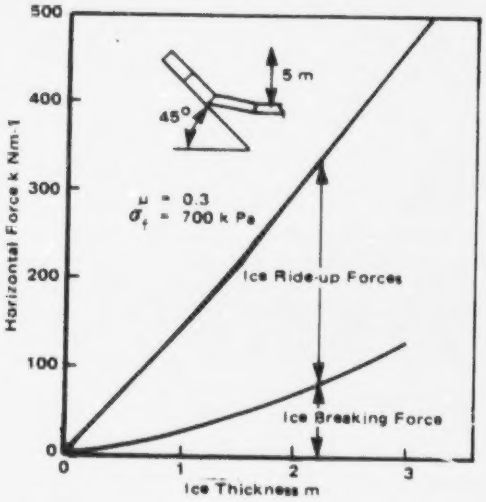
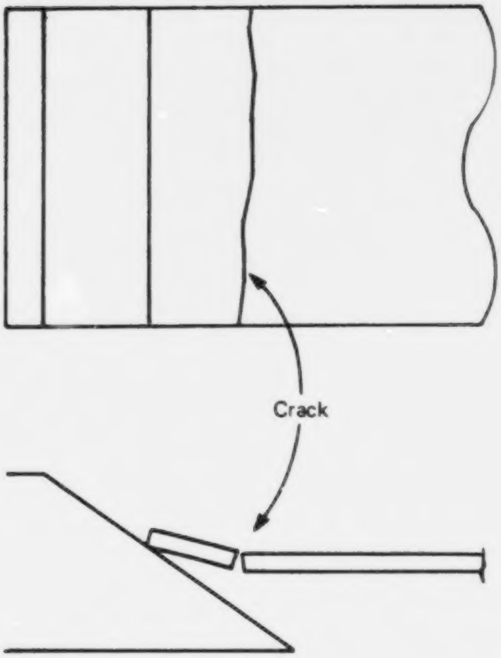
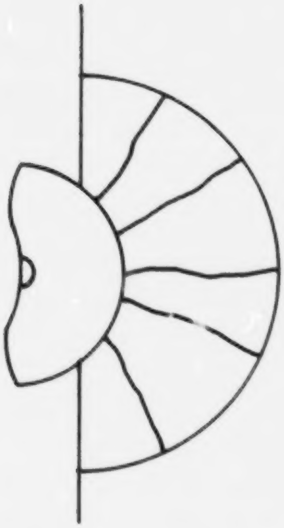


Figure 3.45 Horizontal Force vs Ice Thickness (Simple 2-D Theory)



Simple 2-D Theory

Length of Transverse Crack
Equal to Width of Structure



3-D Theory

Length of Circumferential Crack
Greater than Width of Structure

Figure 3.46 Ice Action on Sloping Structures (3-D Effects)

An approach for ice forces on a conical structure using plastic limit analysis has been proposed by Ralston (1977 - Vol 2, Page 122). His results can be expressed in the form:

$$H = A_4 \; (A_1 \sigma t^2 + A_2 \rho_w g t D^2 + A_3 \rho_w g t (D^2 - D_T^2) \qquad (3.92)$$

$$V = B_1 H + B_2 \; \rho_w g t (D^2 - D_T^2)$$

where D_T is the top diameter and D is the water line diameter. A_1 and A_2 are coefficients dependent on $\rho w g D^2 / \sigma_t$, and A_3, A_4, B_1 and B_2 are coefficients dependent on the cone angle α and friction μ. Values for these coefficients are reproduced in this report in Figure 3.47.

It should be noted that Ralston's analysis includes both the forces due to ice ride-up and ice breaking. In equation 3.92 the first two terms are due to ice breaking and the third term results from the ice pieces sliding over the surface of the cone.

Comparison of Formulae

Correlations have been taken from (Carstens 1980).

As expected, the simple 2-D theory underpredicts the ice breaking component. This is because the structure width is small compared with the characteristic length of the ice sheet. If we adjust the 2-D force by the ratio of the length of the circumferential crack to the structure width, then the force predicted by the 2-D theory agrees better but is still underestimating values compared to Ralston.

Solid Ice Ridges Acting on Sloping Structures

Solid multi-year ridges which occur amongst the polar ice represent a severe loading condition for arctic offshore structures. Multi-year ridges up to 15 m thick are not uncommon and are fully consolidated (Kovacs 1971 - Vol. 2, Appendix 2).

Observations of ridge structure interaction in model tests (Lewis and Croasdale 1978 - Vol. 2, Page 110) indicates that the ridge usually fails first with a centre crack at the point of interaction with the structure (see Figure 3.48). Using simple beam theory the vertical load necessary to cause this initial crack is given by:

$$V_1 = \frac{4 \, I \sigma}{y \ell} \qquad (3.93)$$

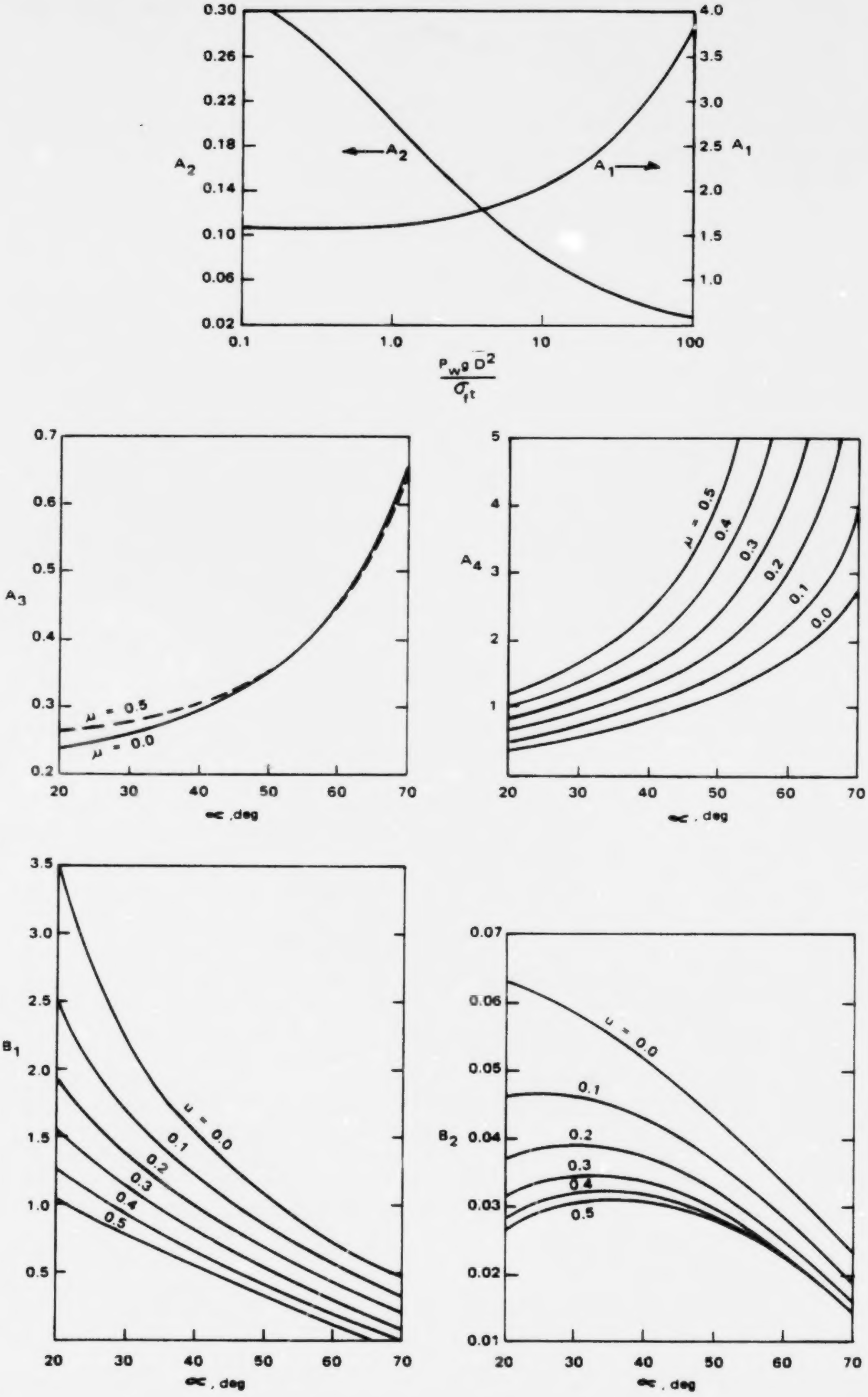


Figure 3.47 Ice Force Coefficients for Plastic Analysis (Ralston 1977)

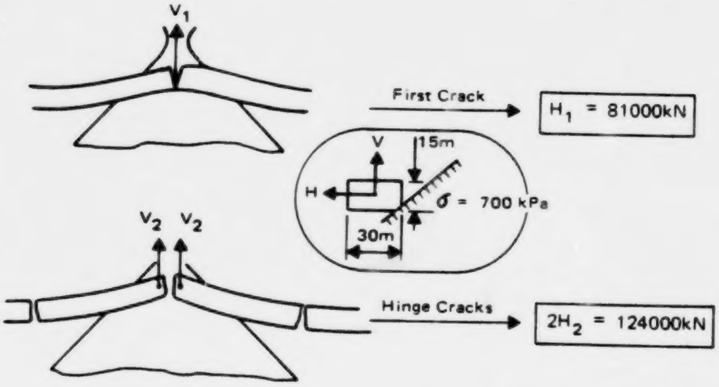


Figure 3.48 Ridge Failure on Cone

where I is the second moment of the area of the ridge cross-section about its neutral axis, σ is the ice flexural strength, y is the distance to the surface in tension (in this case the top surface) and ℓ is the characteristic length given by:

$$\ell = \left(\frac{4EI}{\rho g b}\right)^{0.25} \qquad (3.94)$$

where b is the width of the ridge.

Although when the first centre crack has occurred, the ridge can be considered broken, it cannot pass around the structure without further breaking. Again, observations of tests indicate that the subsequent interaction mechanism is the formation of hinge cracks as shown in Figure 3.48. The vertical force to cause the hinge cracks is calculated by considering the simultaneous failure of two semi-infinite beams on elastic foundations, that is:

$$V_2 = \frac{6.17\ I\alpha}{y\ell} \qquad (3.95)$$

In this case y is the distance from the neutral axis to the bottom of the ridge.

The corresponding horizontal forces depend on the cone angle and ice-to-structure friction, that is:

$$H_1 = V_1 \left(\frac{\sin\alpha + \mu\cos\alpha}{\cos\alpha - \mu\sin\alpha}\right) \qquad (3.96)$$

$$H_2 = V_2 \left(\frac{\sin\alpha + \mu\cos\alpha}{\cos\alpha - \mu\sin\alpha}\right) \qquad (3.97)$$

Typical horizontal forces are shown in Figure 3.48 for the ridge described above acting on a 60° cone with $\mu = 0.3$.

More sophisticated analyses of ridge loads can be done using a more realistic ridge cross-section to calculate I and y. Also, the equations given above are for an infinitely long ridge. Ralston (1977 - Vol. 2, Page 122) has pointed out that shorter ridges can cause greater loads than infinitely long ridges.

Unconsolidated Ice Ridges

First-year ridges are largely unconsolidated, that is, they are composed of ice blocks held together by buoyancy, gravity and frictional forces. The ice is a granular material with an assumed friction angle and the ice force can be caluclated approximately. Hits by end are the most dangerous, but lateral collisions are more common.

For the arrangement shown in Figure 3.49 (ignoring the ridge sail):

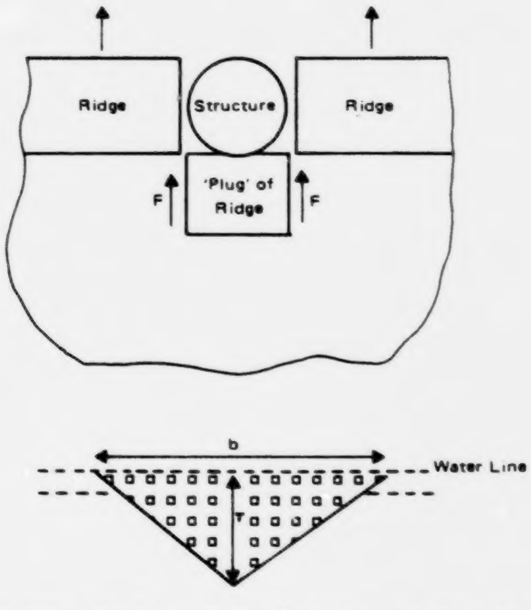


Figure 3.49 Simple Interaction Model Unconsolidated Ridge

$$\text{Force on structure} = 2F = \frac{2BT^2}{3} \rho bg \tan \phi \times C \qquad (3.98)$$

Where C is geotechnical coefficient. It could be assumed at rest for lateral collision.

Where B is the ridge width, t is the ridge thickness σb is the buoyant density of the ice and ϕ is the friction angle of submerged blocks.

As an example, consider an unconsolidated ice ridge 15 m thick by 30 m wide with $\phi = 30°$, and $\sigma bg = 981$ Nm^3, $C = 0.5$:

$$2F = (670)\ 1285\ kN \qquad (3.99)$$

This is about one tenth the load due to a multi-year ridge of the same dimensions. For end collision by the same formation, we may write:

$$F = \frac{Bt^2}{3} \sigma bg \times C_p \qquad (3.100)$$

which gives a force of 5800 kN.

Adfreeze Forces

From Carsten (1980) it is noted that in the nearshore arctic environment the ice surrounding a structure can remain stationary long enough for the ice to freeze to the structure. Also, vertical motions of the ice due to tidal action can be so small that an adfreeze bond can develop between the ice sheet and the structure. Once the ice sheet starts to move again, sliding motion between ice and structure first requires breaking the adfreeze bond. For certain types of sloping structures the force required to fail the adfreeze bond can be significantly greater than force needed to fail the ice in bending. In these situations the force to fail the adfreeze bond can become the design force for the structure.

In the arrangement shown in Figure 3.50 the adfreeze force is given by:

$$H = \frac{\pi tqD}{\tan\alpha} \qquad (3.101)$$

where t is the ice thickness, α is the slope angle, D is the structure diameter and q is the adfreeze bond strength.

Little data is available on adfreeze strengths. Adhesion strengths published by Michel (1970 - Vol. 2, Page 115) are in the

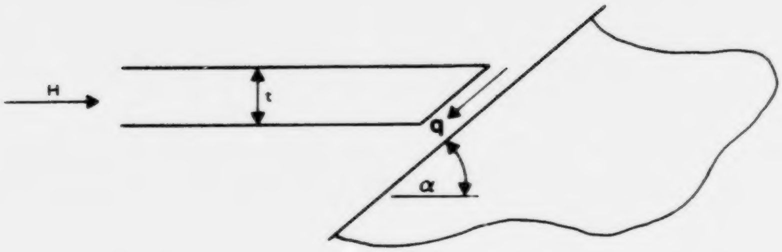


Figure 3.50 Adfreeze Bond Failure

range 140 to 1050 kPa (20 to 150 psi) for fresh ice. More recently Sackinger and Sackinger (1977 - Vol. 2, Appendix 2) have published adfreeze strengths for sea ice on steel. They found that salinity and temperature affected adfreeze strengths. A maximum value of 1590 kPa (227 psi) was measured at a temperature of -23°C for ice with a salinity of 0.4 parts per thousand. See section 3.2.4.

Ice Forces on Mounds and Causeways

A reference is made to the relatively complete treatment in IAHR Guidelines.

Artificial islands are being used in the shallow waters of the Arctic Ocean for oil and gas exploration (Croasdale and Marcellus 1978 - Vol. 2, Page 71). These islands are generally quite wide relative to the ice thickness and therefore the mechanics of ice clearing tends to dominate the ice to structure interaction. Islands and wide structures become surrounded by extensive ice rubble fields which can ground. These rubble fields have to be considered when assessing ice forces (Kry 1978 - Vol. 2, Page 106).

Ice Ride-Up on Berms and Causeways

Low freeboard structures with shallow slopes are susceptible to ice encroachment onto their working surfaces. Ice movement against such structures leads either to ice pile-up in front of the structure or to ice ride-up. The nature of simple ice ride-up is illustrated in Figure 3.51. With ice ride-up, not only can ice encroach onto the working surface, but it advances at the speed of movement of the surrounding ice field. In many cases this would give little time for evasive action.

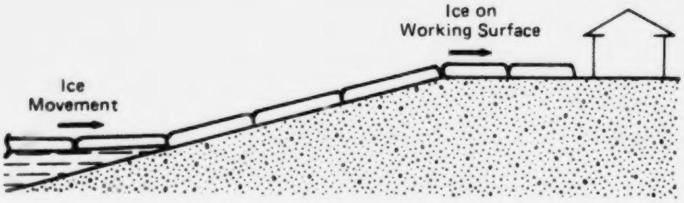


Figure 3.51 Simple Ice Ride-up

When designing low freeboard structures with sloping beaches such as artificial islands, it is important to be able to assess the likelihood of ice ride-up. This section examines factors which may limit ice ride-up, and suggests procedures for designing against ice ride-up.

The history of ride-ups is discussed in the IAHR Guidelines.

Factors Limiting Ice Ride-Up

Ride-up can only occur if the capacity of the ice sheet to push is greater than the resistance to movement of ice up the slope. Ice push can be limited either by the environmental driving force or by the strength of the ice sheet immediately in front of the beach. Resistance to ice sliding up the beach can be caused by instability of the broken ice pieces on the beach slope. These limiting factors are discussed.

Simple Slope Resistance

Consider the configuration shown in Figure 3.52 where P is the force necessary to move the ice pieces up the slope.

Now if:

w is the mass of each ice piece;
n is the number of ice pieces on the slope;
α is the angle of the slope from the horizontal;
μ is the coefficient of friction;
g is the acceleration due to gravity;

then:

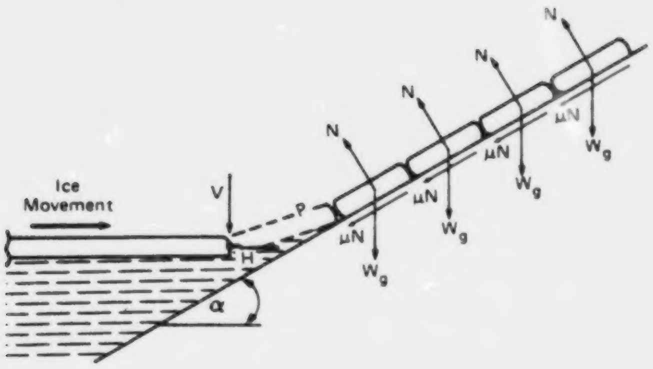


Figure 3.52 Forces for Simple Ride-up

$$P = \sum_{1}^{n} wg\ (\sin\alpha + \mu\cos\alpha) \qquad (3.102)$$

In another form, for a simple two-dimensional system:

$$P = Ltb\rho g\ (\sin\alpha + \mu\cos\alpha) \qquad (3.103)$$

Where, L is the length of slope covered by ice, t is the ice thickness, ρ is the density and b is width of the ice on the slope.

If the steady state environment driving force (F) is greater than the horizontal component of the slope resistance then the potential for ice ride-up exists.

That is, the potential for ice ride-up exists if:

$$\frac{F}{P\cos\alpha} > 1 \qquad (3.104)$$

As an example of slope resistance, consider a beach with a slope angle of 15°, 30 m long, 100 m wide, ice 1 m thick, and a coefficient of friction of 0.3. Then from equation 53, P = 14.6 MN.

The horizontal component, converted to an ice stress = 141 kPa (20 psi).

The work done against gravity and friction in moving ice up the slope can be derived using simple calculus and is given by:

$$U = 0.5\ tb\rho g\ (\sin\alpha + \mu\cos\alpha)\ L^2 \qquad (3.105)$$

where t is the ice thickness, b is the ice width, ρ is the ice density, α is the slope angle, μ is the coefficient of friction, L is the length of slope covered by ice, and g is the gravitational constant.

The initial kinetic energy of the moving floe is given by:

$$KE = (1/8)\ \pi D^2\ t\rho v^2 \qquad (3.106)$$

where D is the diameter of the floe and v is its initial velocity.

For ice ride-up to the top of the slope, $\frac{KE}{U} > 1$, that is:

$$\frac{\pi D^2 v^2}{4bL^2 g\ (\sin\alpha + \cos\alpha)} > 1 \qquad (3.107)$$

Note that the above criterion ignores the work done in bending failure of the ice sheet, but for a long shallow beach this contribution will be small. In any case, ignoring the work done to fail the ice will yield a conservative result.

Hence in this case ride-up by this individual floe is not possible unless other floes impact it from behind and continue to push it against the beach. The critical diameter of an individual floe or which ride-up in this example is possible is 700 m.

Ice Sheet Failure

Although the force necessary to push the ice pieces up the beach is caused by the environmental driving force, it is the ice sheet just in front of the beach which transmits the force. If the force due to slope resistance causes edge failure of the ice sheet then pile-up will occur at the water line and ride-up will be inhibited.

Ice sheet failure can be calculated from formulas for all the sloping faces described above.

Kinematic Instability

For ice to continue to ride-up past a change in slope, certain geometric criteria have to be satisfied, otherwise a kinematic instability can occur. Consider Figure 3.53 illustrating what might happen at the top of a slope, and also at a point of change in angle of the slope. It will be seen that as the first ice block advances past a change in slope it can tilt clear of the

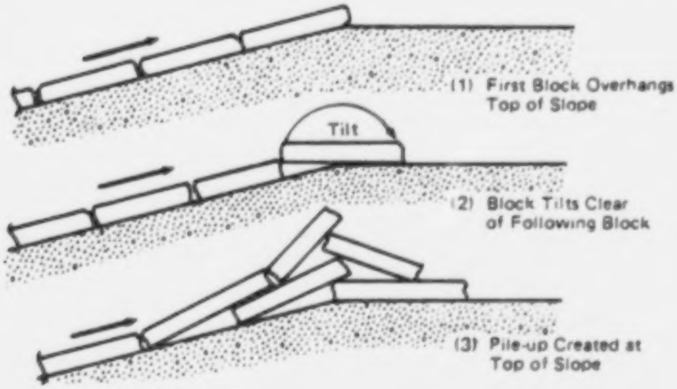

(1) First Block Overhangs Top of Slope
Tilt
(2) Block Tilts Clear of Following Block
(3) Pile-up Created at Top of Slope

Figure 3.53 Kinematic Instability (Pile-up at Top of Slope)

following block thus enhancing the likelihood of a pile-up. However, such an instability can only occur if the ice is thin relative to the change in slope. As shown conceptually, Figure 3.54 if the ice thickness is great enough, then contact between ice blocks is maintained and the ice can continue to advance.

The limiting relationships between ice thickness, block length and slope angle can be derived as follows:

$$h = \frac{\ell \sin\alpha}{2} \qquad (3.108)$$

If $h < t$ then ride-up can continue.

In reality local edge failure will probably occur if the point of contact is too close to the corner. Thus a more realistic condition might be:

$h < 0.8\ t$

Therefore, condition for ride-up to continue is given by:

$t > 0.63\ \ell \sin\alpha$ (3.109)

This limiting condition is plotted in Figure 3.54. For the curve shown the length of the ice pieces is assumed to be three times the thickness. Other curves can be drawn for different length to thickness ratios.

Figure 3.54 suggests that for ice one metre thick a change in slope of greater than 30° would be needed to cause an instability for this mechanism. For a 1 in 3 (20°) slope, ice one metre thick would continue past the top of the slope without a pile-up starting. The ice would have to be less than 0.25 m thick for a pile-up to be generated. For longer ice pieces the critical thickness would be greater.

Compression Instability

If the ice pieces are disturbed out of the plane of the slope as they ride-up, a compression instability may develop.

Consider the configuration shown in Figure 3.55 where e is the height of a 'bump' in the slope. Simple equations of equilibrium can be used to relate P to e at the limiting condition of instability.

If for the purpose of this discussion we set α equal to zero and consider a frictionless, two-dimensional system, then:

$$P = S = \frac{\ell^2 bt\rho g}{2e} \qquad (3.110)$$

or

$$\sigma_c = \frac{\ell^2 \rho g}{2e} \qquad (3.111)$$

where σ_c is the compressive stress in the ice at the point of instability.

Consider the example of ice pieces 4 m long and 1 m thick riding up a slope 30 m long at a 10° angle with a coefficient of friction of 0.3. What would be the height of the eccentricity or 'bump' required to initiate instability and hence a pile-up before the ice pieces reached the top of the slope?

Use equation (53) to calculate simple slope resistance in terms of an ice compressive stress.

$$\sigma_c = (30)\ 900(9.810(\sin 10 + 0.3 \cos 10)\ \mathrm{Pa} \qquad (3.112)$$

$$\sigma_c = 125\ \mathrm{kPa}$$

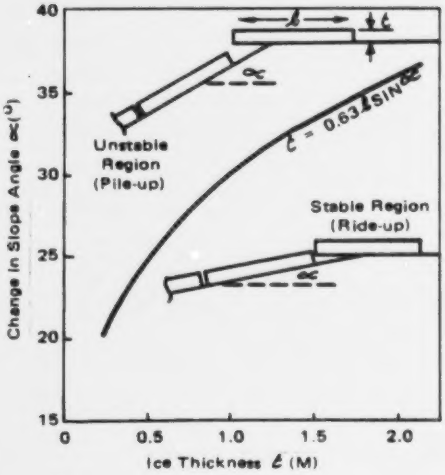


Figure 3.54 Criterion for Ride-up Past a Change in Slope

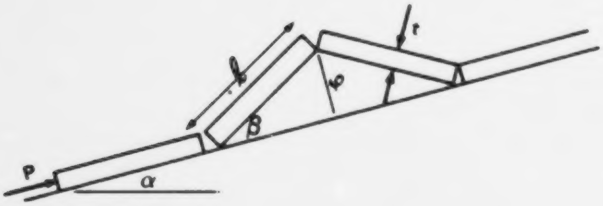


Figure 3.55 Compression Instability

To calculate the value for e:

$$e = \frac{(4)^2(900)9.81}{2(125)1000} = 0.57 \text{ m} \qquad (3.113)$$

That is, a 'bump' say 1 m high at the lower end of the slope would lead to a pile-up being generated before the ice pieces could ride-up to the top of the slope.

Jamming

On beaches which have a sudden steepening of slope angle it is possible for the ice to 'jam' at the point of increasing steepness (Figure 3.56). Jamming leads to a sudden increase in slope resistance which can then cause ice pile-up by one of the mechanisms already discussed.

By using simple equations of equilibrium an expression for P can be derived. In this example, for simplicity assume $\alpha = 0$, then by simple mechanics:

$$P = \frac{W}{2} \left(\mu + \frac{\sin\phi + \cos\phi}{\cos\phi - \sin\phi}\right) \qquad (3.114)$$

The nature of the above equation is that for a particular value of μ a value of ϕ exists for which P becomes infinite and this is the jamming situation.

The 'jamming' situation is governed by the equation:

$$\phi = \tan^{-1} \left(\frac{1}{\mu}\right) \qquad (3.115)$$

Variables of $\phi°$ for typical values of μ are given below.

μ	0.1	0.2	0.3	0.4	0.5	0.7
ϕ (°)	84	79	73	68	63	55

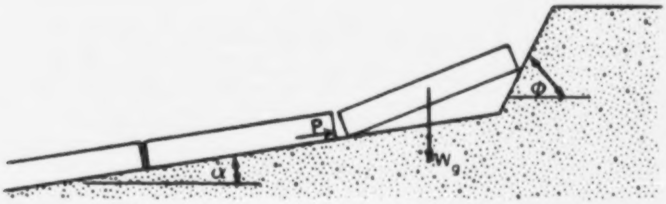


Figure 3.56 Potential Jamming of First Ice Block at Change of Slope Angle

Size Effects

Size effects in loading have been treated by several authors, notably by Slomski and Vivatrat (Vol. 2, page 138).

A Probabilistic Model

First, a distinction will be made between a "breakout" loading condition and a "continuous crushing" condition. The breakout condition refers to the situation in which the ice around a structure (or an indenter) starts to move from an essentially unstressed state. If there is a good initial contact between the indenter and the ice, the pressure- displacement curve will perhaps follow a pattern similar to one of those shown in Figure 3.57. Thus, the pressure will increase rapidly to a very high peak value, corresponding perhaps to a stage of fracture or crack propagation in the ice. After this, it fluctuates in the range of 5 to 35% of the peak value.

A continuous crushing condition can perhaps be said to be analogous to a sequence of the behaviour patterns shown in Figure 3.57. But, because of the continuous movement and fracturing, irregular contacts tend to occur, resulting in some locations being at peak pressure while others are before or beyond the peak pressure.

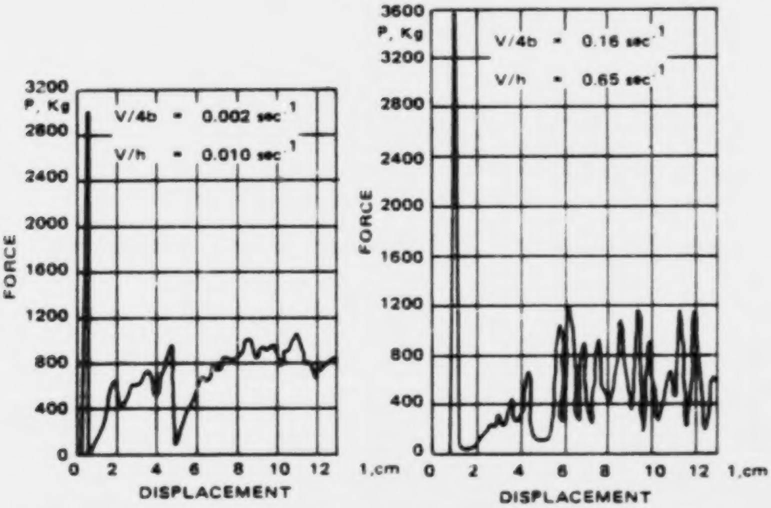


Figure 3.57 Force (or Pressure) vs. Displacement from Identation Tests

In order to estimate the possible effects of this phenomenon for application to floe impact problems in the Beaufort Sea, the values of the peak indentation pressure for summer impact were estimated, and a simplified pressure-displacement curve postulated (Figure 3.58).

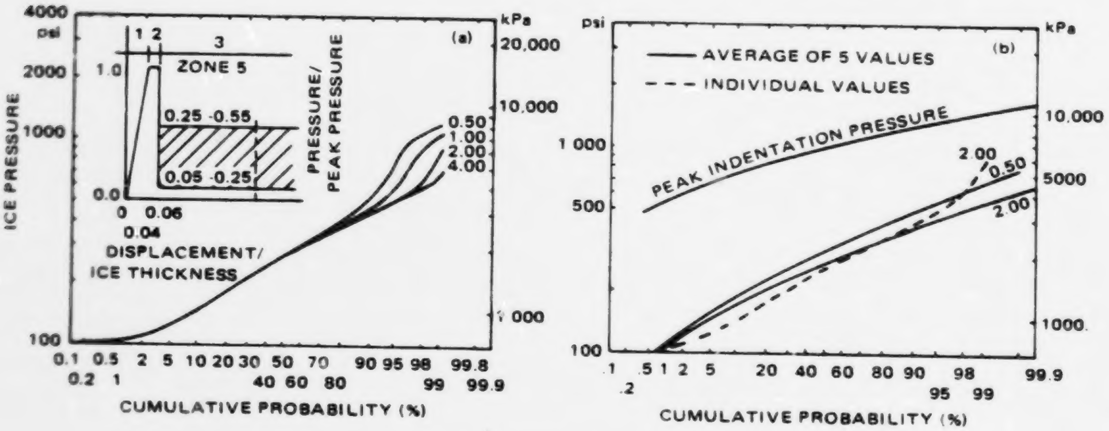


Figure 3.58 A Probabilistic Model of Nonsimultaneous Occurrence of Peak Pressure

Design Ice Pressure

Figure 3.59 drawn on the basis of Slomski and Vivatrat (1983 - Vol. 2, page 138) shows the value of the effective ice pressure at cumulative probabilities of 99% and 95% of all impact events for various contact area sizes. The values for contact area larger than 300 m^2 (3200 ft.^{2}) become quite small since very few simulated events involve contact area that large.

A suggested design curve is drawn on the basis of these predictions. For smaller contact areas, values based on the peak indentation pressure (Figure 3.60) were tentatively selected pending further investigation. The suggested design pressure is 5700 kPa (830 psi) at 90 m^2 (1000 ft.^{2}) and 3450 kPa (500 psi) at 300 m^2 (3200 ft.^{2}) and is similar to that suggested by Bruun et al. (1982 - Vol. 2, Page 268) on the basis of physical reasoning. Also shown in Figure 3.59 is a curve showing the possible effects of winter contact with multi-year floes.

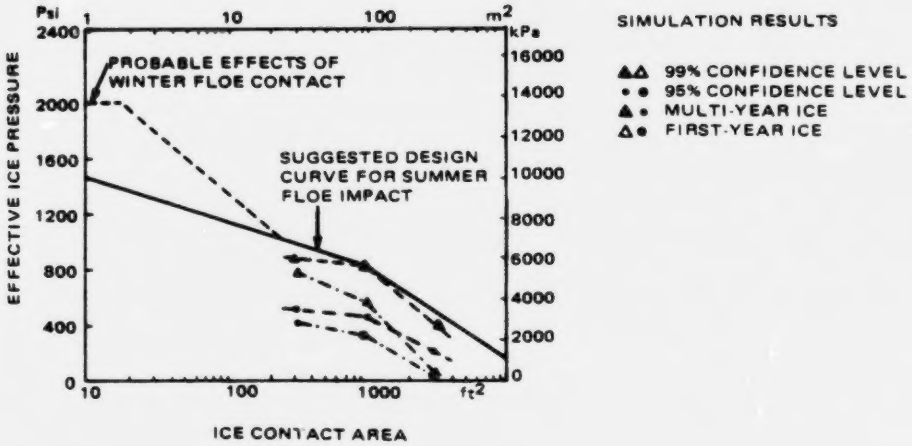


Figure 3.59 Predicted Effective Ice Pressures and Suggested Design Curve

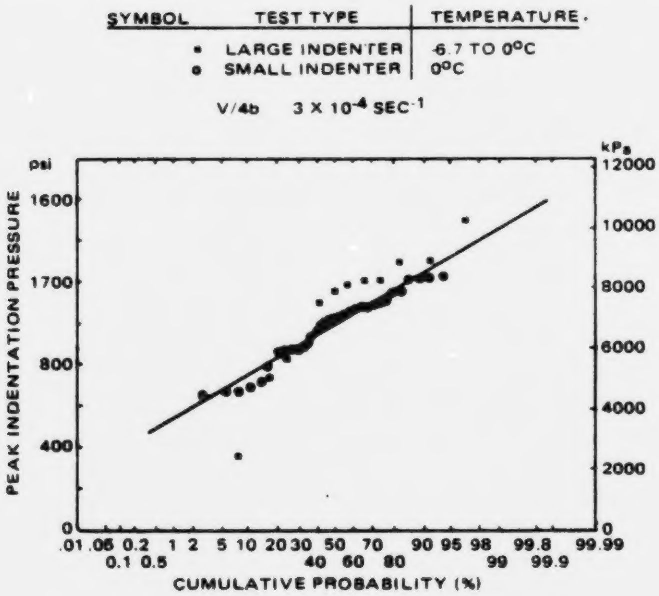


Figure 3.60 CDF of Peak Indentation Pressure for Tests at High Strain-Rate and Warm Temperature

3.4.3.3 Buckling of the Transmitting Media

For a thorough review, reference is made to Sodhi and Nevel in the IAHR review (Carstens 1980 - Vol. 2, Appendix 2). Since buckling is a possible mode of failure for an ice sheet as it impinges on a vertical structure, it is necessary to study the buckling of floating ice sheets, which have been analyzed as beams or plates resting on elastic foundations. The force offered by the elastic foundation is assumed to be linearly proportional to the deflection of the ice sheet, an assumption that is valid as long as the ice sheet does not submerge completely under the water surface or emerge completely out of water. This assumption is also adequate for the linear buckling analysis that determines the load for the incipience of instability, but it is not valid for the post-buckling or dynamic behaviour of an ice sheet.

Sodhi's review is divided in two sections: 1) buckling analysis of beams on elastic foundations; and 2) buckling analysis of plates on elastic foundations.

Buckling Analysis of Beams on Elastic Foundations

Beams of Rectangular Cross-Section

The deflection and buckling analysis of beams on elastic foundations has been presented by Hetenyi (1946 - Vol. 2, Appendix 2). It is summarized briefly here for the sake of completeness.

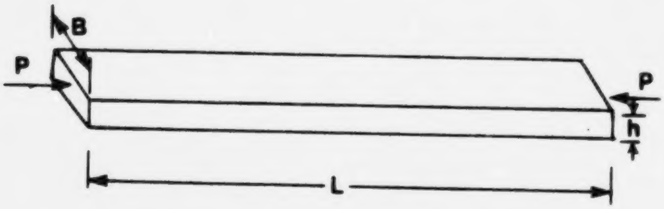


Figure 3.61 Geometry of a Beam with a Rectangular Cross-section Resting on an Elastic Foundation with Compressive Axial Load P

The differential equation governing the buckling of a beam with a rectangular cross-section (Figure 3.61) resting on elastic foundations and subjected to an axial compressive force P can be shown on enclosed graphs.

Sodhi has shown that the buckling load depends explicitly on the boundary conditions imposed at the ends of the beam and implicitly on the length of the beam. A buckling load exists for each mode of buckling of the beam, but we are only interested in the lowest buckling load of a given beam. The lower envelope plots of the non-dimensional buckling pressure $P/(BKL_b{}^2)$ with respect to the ratio of beam length to characteristic length, L/L_b, are given in Figure 3.62 for the six different boundary combinations.

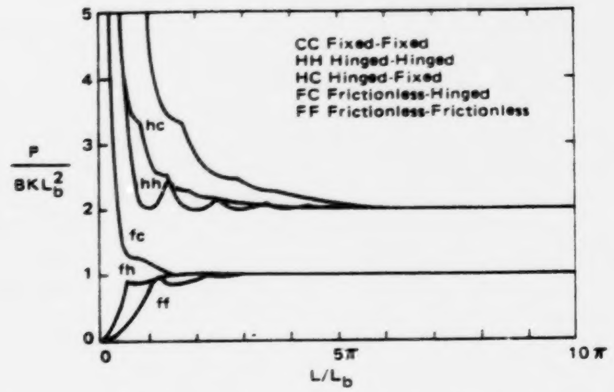


Figure 3.62 Lower Envelope Plots of Non-dimensional Buckling Pressure P/BKL_b^2) with Respect to the Ratio of Length to Characteristic Length, L/L_b.

The buckling analysis of tapered beams is of considerable interest because such a situation may occur when an in-plane force acting on an edge of an ice sheet creates vertical cracks originating from the area of loading and radiating outward into the ice sheet.

In these discussions, the concept of elastic length is introduced. $L_b = (Eh^3/12K)^{1/4}$.

This buckling analysis of tapered beams is valid only for small values of taper angle α, and the use of plate theory would be more appropriate for the cases when α is large.

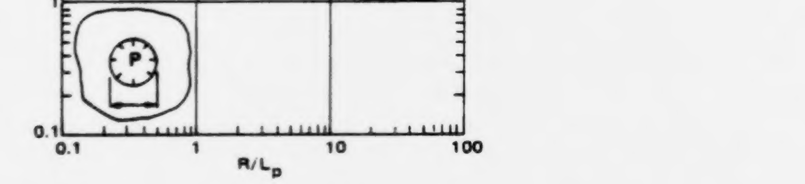


Figure 3.63 Plots of the Lowest Buckling Pressure p/KL_p^2) with Respect to R/L_p for an Infinite Ice Sheet Stressed Uniformly Along the Periphery of an Internal Hole (Takagi, 1978)

Plots of the lowest non-dimensional pressure p/KL_b^2) with respect to R/L_p are given in Figure 3.63 for three boundary conditions imposed at $r = R$ (frictionless, hinged, or clamped). The value of Poisson's ratio ν is taken to be 0.3 in the computation of buckling pressure when a frictionless or hinged boundary condition is specified at $r = R$. The non-dimensional buckling load varies in a similar manner with respect to R/L_p as in the case of tapered beams, but the values are much higher for low values of R/L_p, which may be attributed to the development of hoop stresses around the hole. The asymptote of the buckling pressure for high values of R/L_p is 4 for hinged and fixed boundary conditions and 1.07 for the frictionless boundary condition. The corresponding values for a floating ice beam are 2 and 1.

Special cases of interest are illustrated in Figures 3.64, 3.65 and 3.66 as follows:

The results of the first two studies and a particular case of the third study are presented in Figure 3.67 in the form of plots of $P/(2RKL_p^2)$ with respect to $2R/L_p$, where 2R is the structure width or length over which the load P is distributed. The results of the three studies are close to each other for the frictionless boundary condition, whereas the results of the second study are higher by 40% than those of the third study for the fixed boundary condition. This difference can be explained by noting that the stress field in the ice sheet is not strictly radial when fixed boundary conditions are used to determine the pre-buckling stress field.

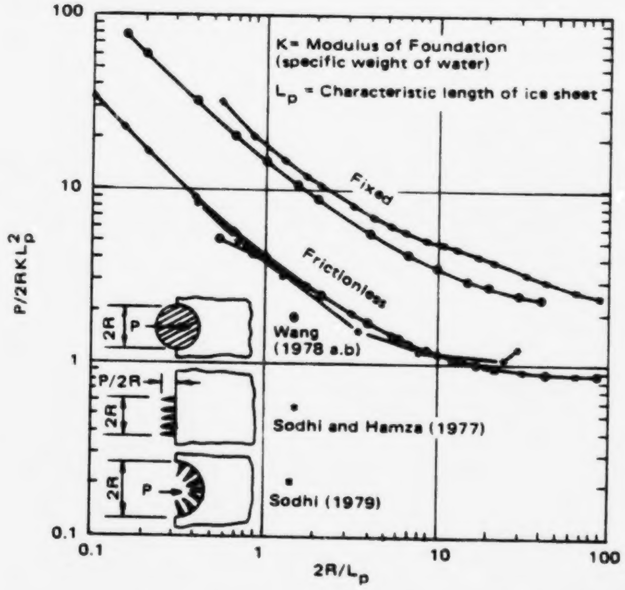


Figure 3.67 Plots of Non-dimensional Buckling Pressure $P/(2RKL_p^2)$ with Respect to $2R/L_p$ for Semi-infinite Ice Sheets (Sodhi and Nevel, 1980)

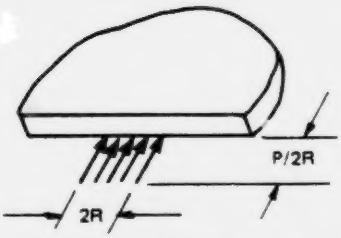


Figure 3.64 Geometry of Semi-infinite Ice Sheet Acted on by a Uniformly Distributed Load over a Finite Length

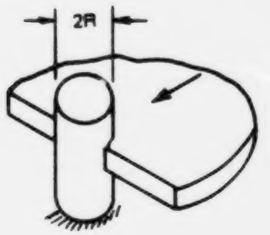


Figure 3.65 Geometry of a Semi-infinite Floating Ice Sheet Moving Against a Rigid Cylindrical Structure

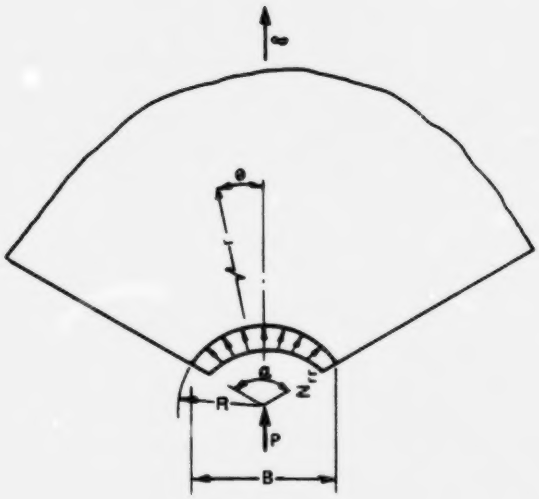


Figure 3.66 Geometry of a Semi-infinite Wedge-shaped Floating Ice Sheet

The results of the third study on the buckling of wedges (Sodhi 1979) are presented in Figure 3.68 in the form of plots of non-dimensional buckling pressure $P/(BKL_p{}^2)$ with respect to R/L_p for different values of wedge angle α and different boundary conditions. Figure 3.69 shows the plots of buckling load $P/(KL_p{}^3)$ with respect to wedge angle α when P acts on a very small area (i.e. P is a concentrated force).

In the study by Sodhi (1979), the buckling analysis is extended to wedges having wedge angles greater than 180°. The results for these cases are shown in Figures 3.70 and 3.71 in the form of plots of $P/(2RKL_p{}^2)$ with respect to $2R/L_p$. The cases considered in these figures differ in the way the total P is distributed in the ice sheets; Figure 3.70 shows the buckling load P creates a compressive as well as tensile stress field, whereas in Figure 3.72 the buckling load creates a totally compressive stress field. The buckling pressure for the second case is lower than that in the first case.

This is a review only of the theoretical analyses of the buckling of (as presented by Sodhi) floating ice sheets in the form of beams and plates resting on elastic foundations. The buckling analysis of uniform cross-section and tapered beams on elastic foundations is presented; the results are presented in graphical form. The buckling analysis of plates on elastic foundations is mainly restricted to semi-infinite ice sheets and wedge-shaped ice sheets; the results of these analyses are also presented in graphical form.

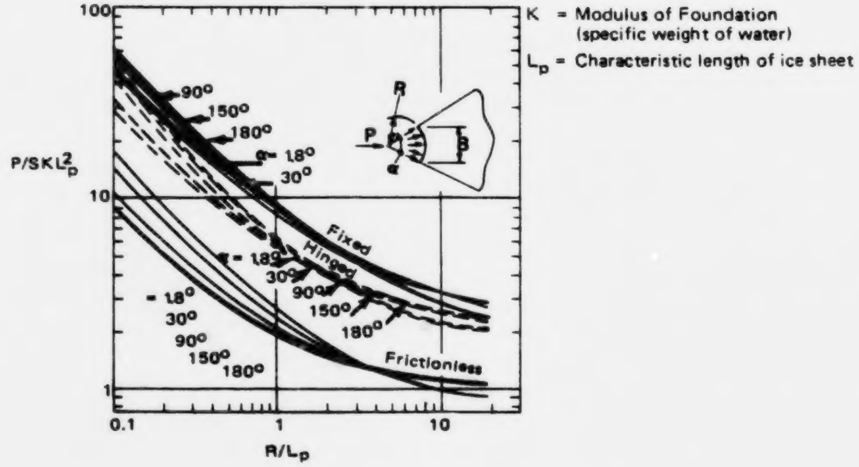


Figure 3.68 Plots of non-dimensional buckling pressure $P/(BKL_p^2)$ with respect to R/L_p for semi-infinite wedge-shaped ice sheets

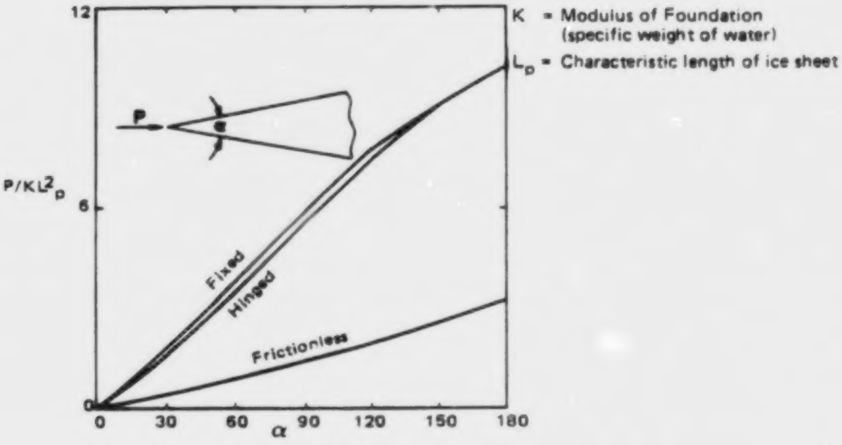


Figure 3.69 Plots of Concentrated Buckling Force $P/(KL_p^3)$ With Respect to the Taper Angle α of Semi-infinite Wedge-shaped Ice Sheets

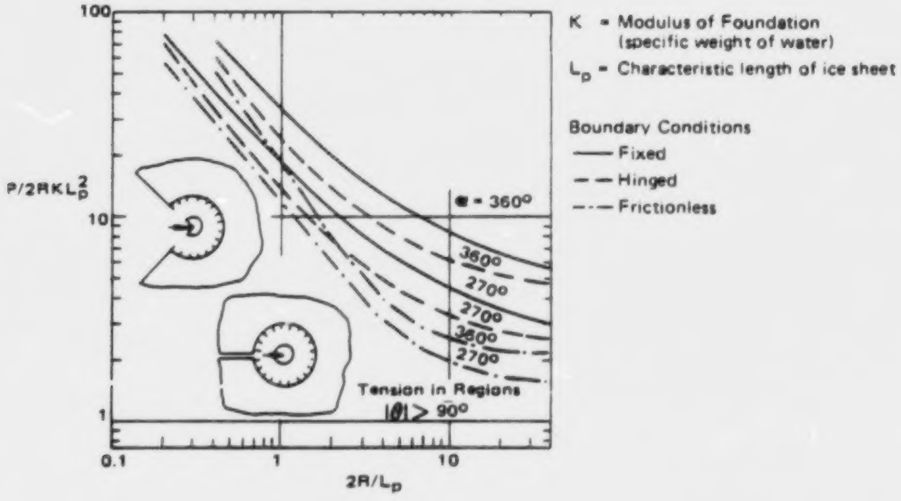


Figure 3.70 Plots of buckling pressure $P/(2RKL_p^2)$ with respect to $2R/L_p$ when wedge-angle α is greater than π and when P creates a compressive as well as tensile stress field

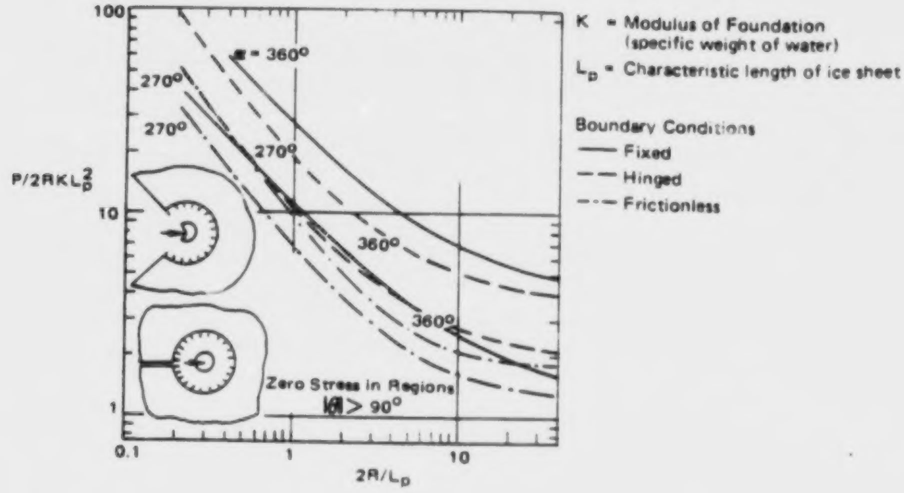


Figure 3.71 Plots of buckling pressure $P/(2RKL_p^2)$ with respect to $2R/L_p$ when wedge-angle α is greater than π and when P creates only a tensile stress field

The buckling pressure of wedge-shaped ice sheets is very high when the aspect ratio (structure width to the characteristic length of the ice sheet) is low, and hence the ice sheet fails in the crushing mode. For high aspect ratios, the buckling pressure is low, approaching the values of buckling pressure associated with infinite beams having the same boundary conditions as wedge-shaped ice sheets. The buckling pressure is strongly dependent upon the characteristic length of the ice, which in turn depends upon the modulus of elasticity of ice.

Often force is transmitted by a broken ice cover or by a pack of floes of broken and solid cover. A general review and comparision of these load cases is shown below.

Stability

Solid Ice Cover

The critical stress σ_{cr} for buckling of a beam on an elastic foundation is as shown by Heternyi (1946) in Beams on Elastic Foundations.

$$\sigma_{cr} = 0.6\ (E\gamma_w h)^{1/2} \qquad (3.116)$$

where γ = unit weight of water (Pwg).

This expression corresponds to an infinitely long beam on an elastic foundation or a finite beam with hinged ends on an elastic foundation (an approximation in the latter case).

If sliding is permitted at one end, σ_{cr} is given by

$$\sigma_{cr} = 0.3 \, (E\gamma_w h)^{1/2} \qquad (3.117)$$

In practice this situation is more realistic than the previous ones.

Broken Ice Cover

During spring, the ice sheet is in a broken state. Stability considerations of the individual broken piece, on the assumption that the piece is hinged at one end and free to slide at the other end (at contact with adjacent pieces), yields the following result (Kivisild and Iyer 1978 - Vol. 2, Page 15):

$$\sigma_{cr} = 0.137 \, (E\gamma_w h)^{1/2} \qquad (3.118)$$

Loose Pack Stability of Floes

If the pack is so loose, sliding is possible at both ends according to Coon. There is an error in Coon's original derivation for σ_{cr}. After necessary correction, the value is found to be as follows (Kivisild and Iyer 1978 - Vol. 2, Page 15):

$$\sigma_{cr} = 0.03 \, (E\gamma_w h)^{1/2} \qquad (3.119)$$

3.5 Structural Response to Continuous Crushing

3.5.1 Artificial Islands

Croteau et. al. (1983 - Vol. 2, Page 73) used an energy balance algorithm (Table 3.9) to investigate the impact of 300 and 1800 m ice floes against 90 and 120 m diameter caisson retained gravity platforms on various soil type foundations located in 10 to 20 m of water. A summary of his results are presented below:

1. The dependence of ice strength upon strain rate had a significant influence on the amplitude, duration and shape of the force pulse. It was noted that a sharp increase in load level occurred near the end of the impact as the relative velocity approached zero.

2. The slope of the elastic portion in the force-penetration relation used in the ice element formulation was of little significance for these types of impact problems considered in this chapter.

3. As in most cases involving dynamic response to impulsive loads, the peak response was primarily dependent upon the force duration with respect to the natural period of the structural system.

4. In analysing elastic response to ice floe impacts, the energy-balance method yields a force time variation essentially identical to that obtained in the dynamic analysis for all but very short impact events. The inertia of the structure-foundation system absorbs part of this applied force such that the response quantities (base shear, overturning moment and displacements) were somewhat lower than those computed quasi-statically when strain rate effects were considered.

5. When the strain rate effect on ice strength is ignored, however, the response is found to be essentially quasi-static for the cases studied, particularly for impact events involving very large features for which the pulse duration is long compared to the period of the system.

Concerning response sensitivities to physical parameter variations, the following relationships were found:

1. The geometry of the ice-structure interface has an important influence in determining the shape of the ice force pulse; it should be noted, however, that the geometry producing the slowest rate of force buildup (an inclined wall was considered as an example) may not necessarily yield the minimum peak ice force, particularly if a large amount of penetration takes place; hence providing protrusions at the face of a structure might not always be effective.

2. If the floe is assumed to fail in flexure or if a contact pressure characteristic of rubble forming is assumed to apply during an impact event, the impulse is found to last tens of seconds instead of seconds and the load level is reduced by a factor of 2.6 to 13.9 compared to the response obtained by assuming a crushing interaction.

3. Soil condition variations do not significantly affect the ice force developed at the contact point in elastic systems, for impact events of the intensity considered by Croteau. However, when the structure-foundation system undergoes plastic deformation, the ice force time history is significantly affected by the fact that energy is no longer dissipated only in breaking the ice but also in plastic work in the soil.

4. In non-linear structure-soil systems, the relative velocity at the ice-structure interface is very low, in the ductile range, as most of the slippage and permanent tilting are taking place.

1. Initialize force, energy, penetration, velocity, strain rate, time; compute kinetic energy:

   $P_o = 0 \qquad V = V_o$
   $E = 0 \qquad e = 0$
   $x = 0 \qquad t = 0$

   $$U = \frac{1}{2} M_I V_o^2$$

2. Increment penetration:

   $$x = x + dx$$

3. Compute dimensions of contact area:

   $t = t\ (x)$
   $b = b\ (x)$

4. Compute ice force (identation factor, ice strength, pressure, force:

   $C_I = C_I\ (b,t)$

   $f_c = f_c\ (\dot{e})$
   $p = C_I m k f_c$
   $P = p\ bt$

5. Update energy dissipation, assuming linear variation of force during displacement increment:

   $$E = E + \frac{1}{2}\ (P + P_o)$$

6. If $E \geq U$, computation completed.

7. Update velocity, strain rate:

   $$V = \left(\frac{2(U-E)}{M_I}\right) 0.5 \qquad \dot{e} = \frac{V}{2\ b}$$

8. Compute time, assuming linear variation of velocity:

   $$t = t + \frac{2\ dx}{V + V_o}$$

9. Reset initial parameters for next penetration step:

   $V = V_o \qquad P = P_o$

   and go to 2. For further details see Croteau (1983).

Table 3.9 Algorithm for Energy-Balance Ice Impact Computations

5. For the cases analysed, lower peak accelerations are computed for the case involving a very large ice floe (platform "C") than for a smaller size flow; maximum accelerations at the deck level were found to attain nearly 0.20 g which might be significant in designing topside facilities.

6. For the circular floe and platform geometries assumed, the maximum torque developed in an eccentric impact was found to be produced when the point of contact is offset by a distance equal to about 0.65 to 0.75 times the structure radius; the maximum torque amplitude may be roughly computed by applying the maximum shearing reaction with an offset equal to 0.35 times the platform radius.

In concluding, it is noted that the dynamic response of a gravity platform subjected to open water impacts of the type considered is quite complex and is affected by a number of factors including the ice floe conditions, soil compliances, foundation resistance and eccentricity.

3.5.2 Rigid Structures

Croteau (1983 - Vol. 2, Page 72) used an analytical model to measure the structural response of an isolated top and bottom rigidly fixed hollow steel shaft subjected to continuous crushing from a sheet of ice 1.2 m thick with a peak compressive strength of 1.75 MPa. (A treatment considering rigidity is also found in SNIP II-57-75). The results produced a constant value in the ice force for strain rates in the brittle domain with the corresponding structural response being typical to a suddenly applied load. As the velocity decreased, crushing began to take place in the range where ice strength varies with strain rate, the oscillatory response of the shaft to the initial impact caused the ice force to oscillate. The variation in the forcing function affected the structural response in a fashion similar to an in-phase harmonic loading, producing an increase in the vibration amplitudes which reached a steady state in about 5 sec. A constant pattern in the ice force and displacement traces was then maintained for as long as the ice sheet velocity remained unchanged (Figure 3.72). The response traces of the ice force were shown to exhibit a sinusoidal pattern.

Spike loads activated by the breaking process in ice, described earlier, cause additional stress oscillation in the structure.

Analytical results of bridge pier measurements indicate that foundation reaction quickly dampens out to a constant force level after the initial dynamic response in the brittle domain (Figure 3.73). Slower strain rates result in a smooth curve.

3.5.3 Flexible Structures

Analysis of a flexible, slender structure (in this case a lighthouse) subjected to continuous crushing by a 40 cm ice sheet with a stiffness of 2.8×10^6 kN/m and 2.8×10^5 kN/m were found to have reaction time histories much different from the rigid shaft with a higher amplitude and more saw-tooth like pattern (Figure 3.74). Oscillation periods increased with decreasing ice sheet velocity. On the ice force trace, a high frequency variation (20 to 25 Hz) is superimposed onto this basic ratcheting pattern which in some cases was found to slowly dampen out. At a lower ice stiffness the results indicate that the clear long-period saw-tooth behaviour is not sustained as long as in the case of the stiffer ice.

The principal observation to be made here is the fact that a flexible structure subjected to slow continuous crushing appears to invariably exhibit some form of self-sustained oscillatory behaviour. This is not the case for a rigid pier analysed previously by Croteau (1983) where a stable force and reaction were achieved after the initial dynamic response. It is likely that a useful measure of the "degree" of flexibility might be the ice versus structure stiffness ratio; this ratio was 1.93 for the bridge pier case, 6 for the flexible lighthouse case with the lower-bound assumption and 63 for the lighthouse case with the upper-bound assumption.

It is of interest to recall several remarks made by Peyton (1969 - Vol. 2, Appendix 2) regarding field observations of platform response in the early work at Cook Inlet:

- "(The ratcheting type) mode of ice failure is the source of severest structural loading and occurs with very slow rates of loading...at velocities between virtually zero to 50 feet per minute. Normally impacts are at higher velocities and create higher load frequencies."

- "The ratcheting failure seems to happen only at low ice temperatures..." for which we might add, the ice stiffness is high.

- Also, "a 2:1 ratio of ratcheting induced forces to high velocity induced forces is a consistent value. Clearly, ratcheting is a load rate effect of the ice rather than resonant amplification of structural stresses".

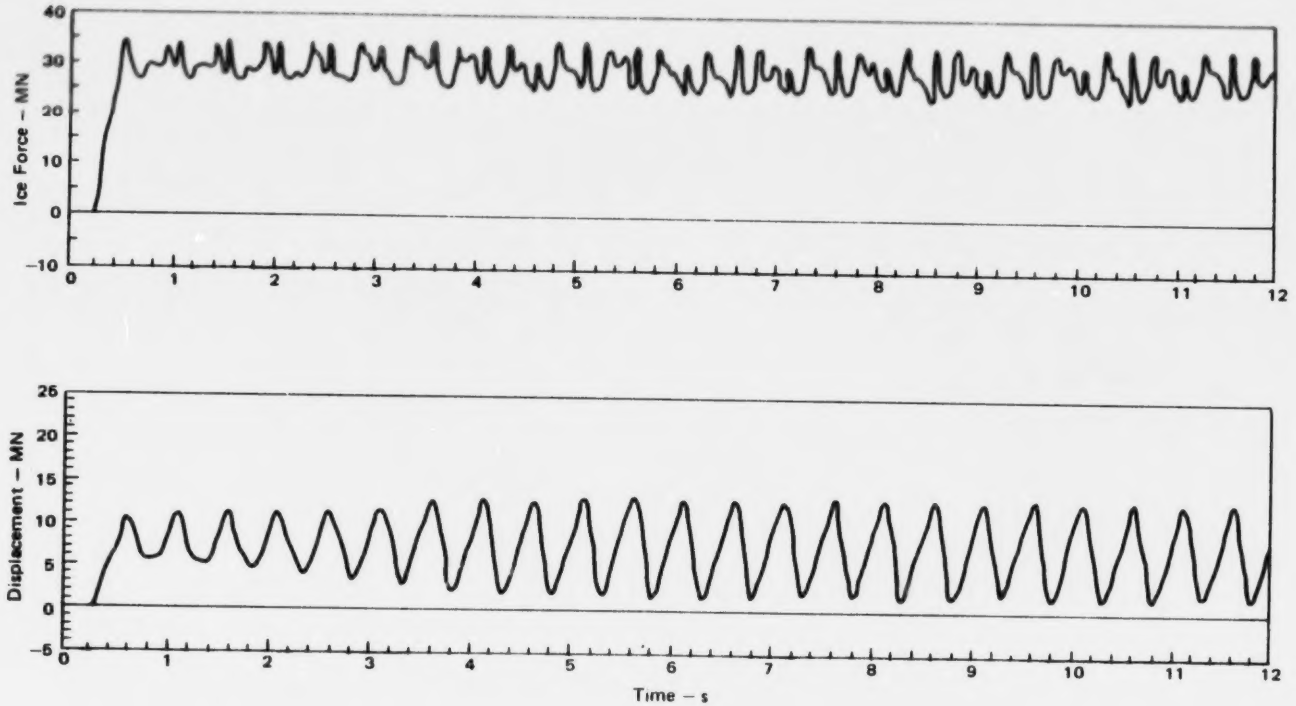


Figure 3.72 Single Shaft Analysis
Ice Force and Waterline Displacement
Development of a Limit Cycle

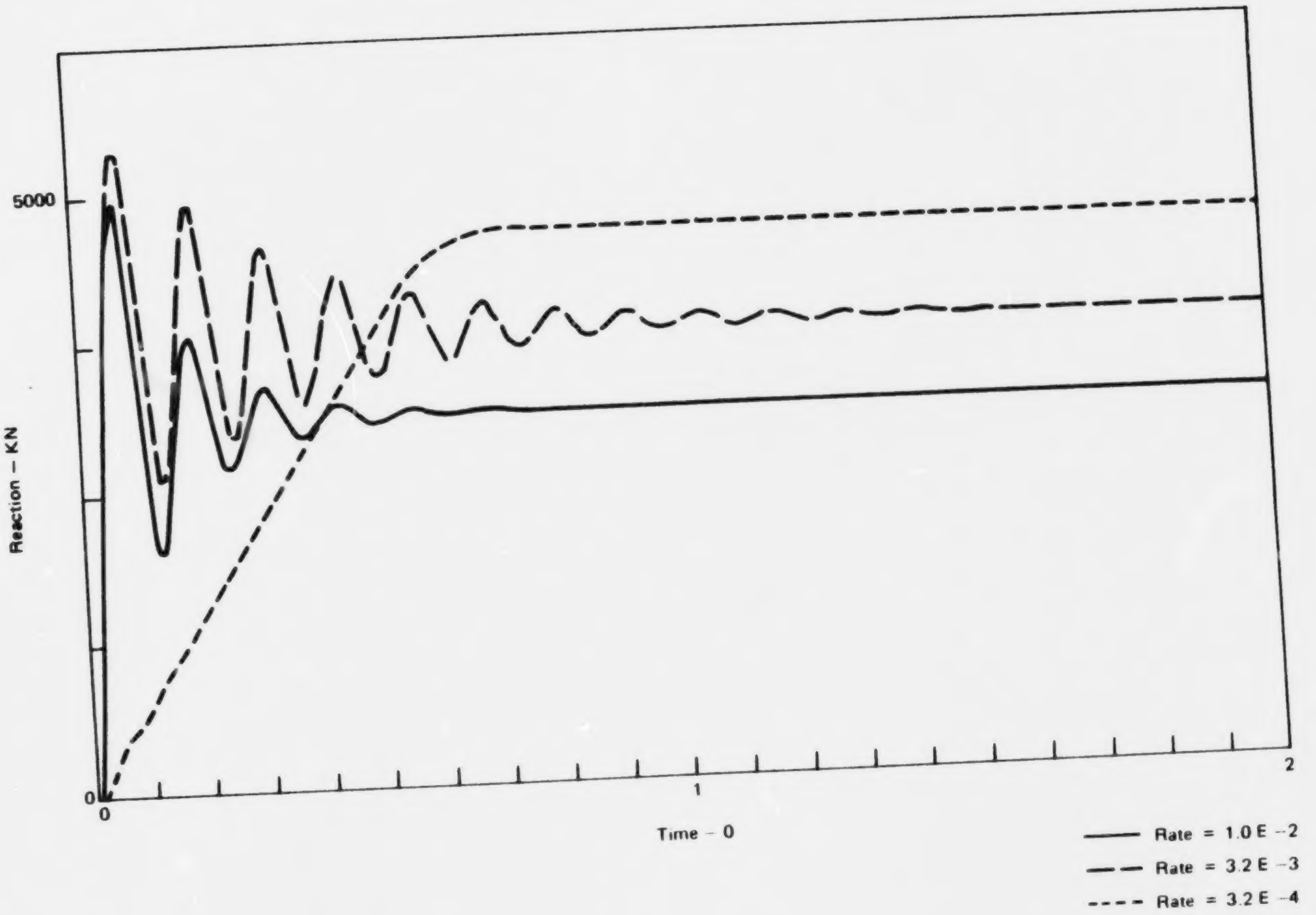
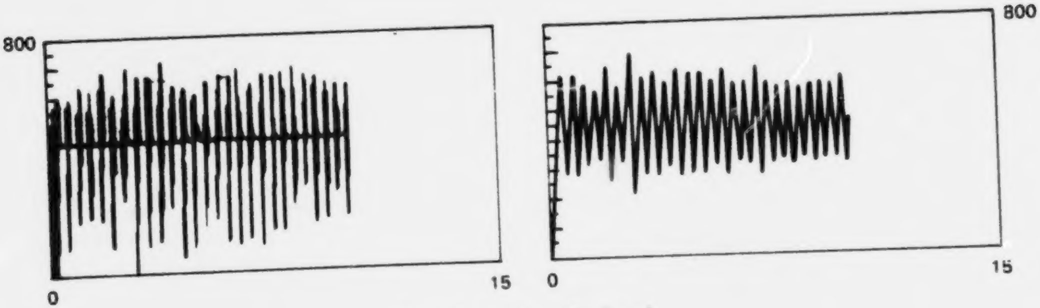
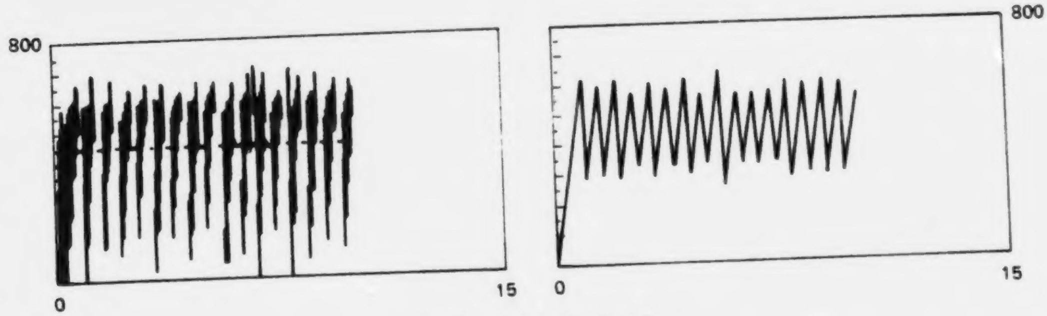


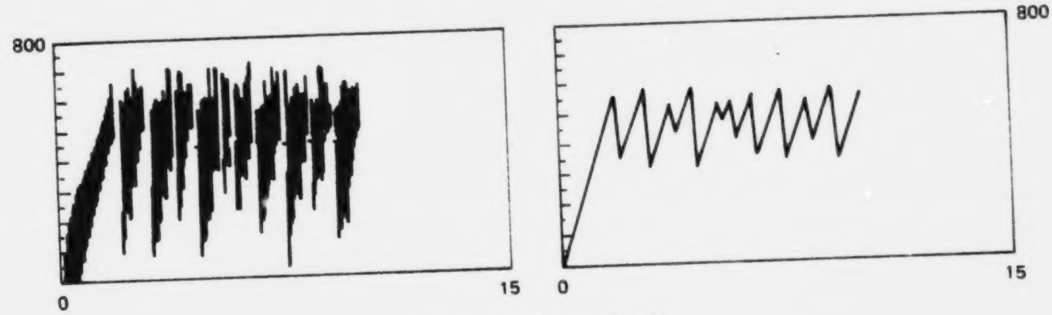
Figure 3.73 Bridge Pier Analysis Foundation Reaction for Varying Strain Rates



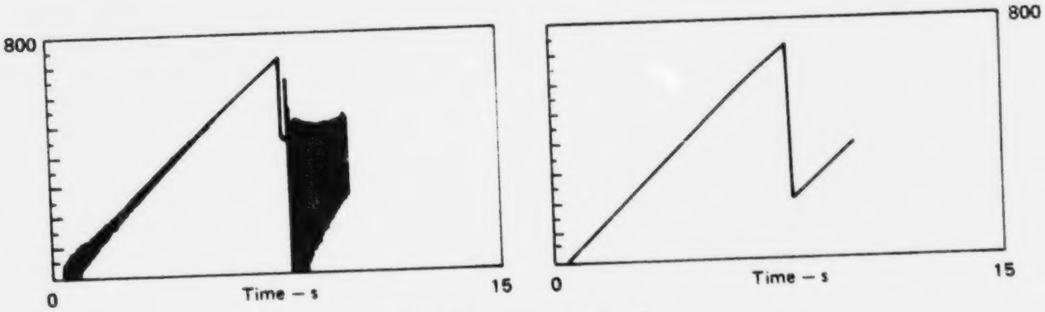
P1 – $\dot{e} = 3.0 \times 10^{-2}\ s^{-1}$



P2 – $\dot{e} = 1.2 \times 10^{-2}\ s^{-1}$



P3 – $\dot{e} = 5.1 \times 10^{-3}\ s^{-1}$



P4 – $\dot{e} = 1.6 \times 10^{-3}\ s^{-1}$

Figure 3.74 Lighthouse Analysis – Strain Rate Variation Ice Force and Reaction for High Value of Ice Stiffness ($2.8 \times 10^{+6}$ KN/m)

CHAPTER 4

ARCTIC GEOTECHNIQUE

4. ARCTIC GEOTECHNIQUE

4.1 Geological Setting and Permafrost Distribution

4.1.1 Physiographic Regions on Northern Coasts

Northern Canada has a very extensive coast line covering a wide variety of terrain types. The coastal areas range from the Northern Yukon in the west to Northern Labrador in the east via Hudson Bay in the center and the Arctic Archipelago.

The conditions on northern coasts have been influenced by several factors such as bedrock geology, glaciation, sea level changes, post glacial rebound and recent erosion and sedimentation. Sea bed conditions and availability of granular construction materials are dependent to a large extent on the above factors. General information on potential sea bed and shoreline conditions, bedrock conditions and borrow materials can be obtained from a review of geological information available from the Geological Survey of Canada.

The northern territories of Canada are divided into seven different physiographic regions (Douglas 1970 - Vol. 2, Page 188) which are illustrated on Figure 4.1.

Each physiographic region is briefly discussed below, specifically with respect to offshore and coastal geology.

Arctic Coastal Plains (1)

The Arctic Coastal Plain is a narrow strip of coastal land extending from Alaska to Meighen Island. Mackenzie Delta is included.

The topography is generally flat with gentle slopes towards the sea. This region has a complex history of uplift and erosion of deltas and other fluvio-marine features. Thick sediment deposits are typical of these coastal areas.

Interior Plains (2)

The Interior Plains include the area between the Mackenzie Delta and the Coronation Gulf near Coppermine. Most of the Mackenzie river system is included in this physiographic region.

The topography has little relief and the general area is at a low elevation. The ground surface is underlain by either bare rock or thin glacial drift. Bedrock is sedimentary of the Paleozoic and late Proterozoic era and may be folded and faulted near the coast.

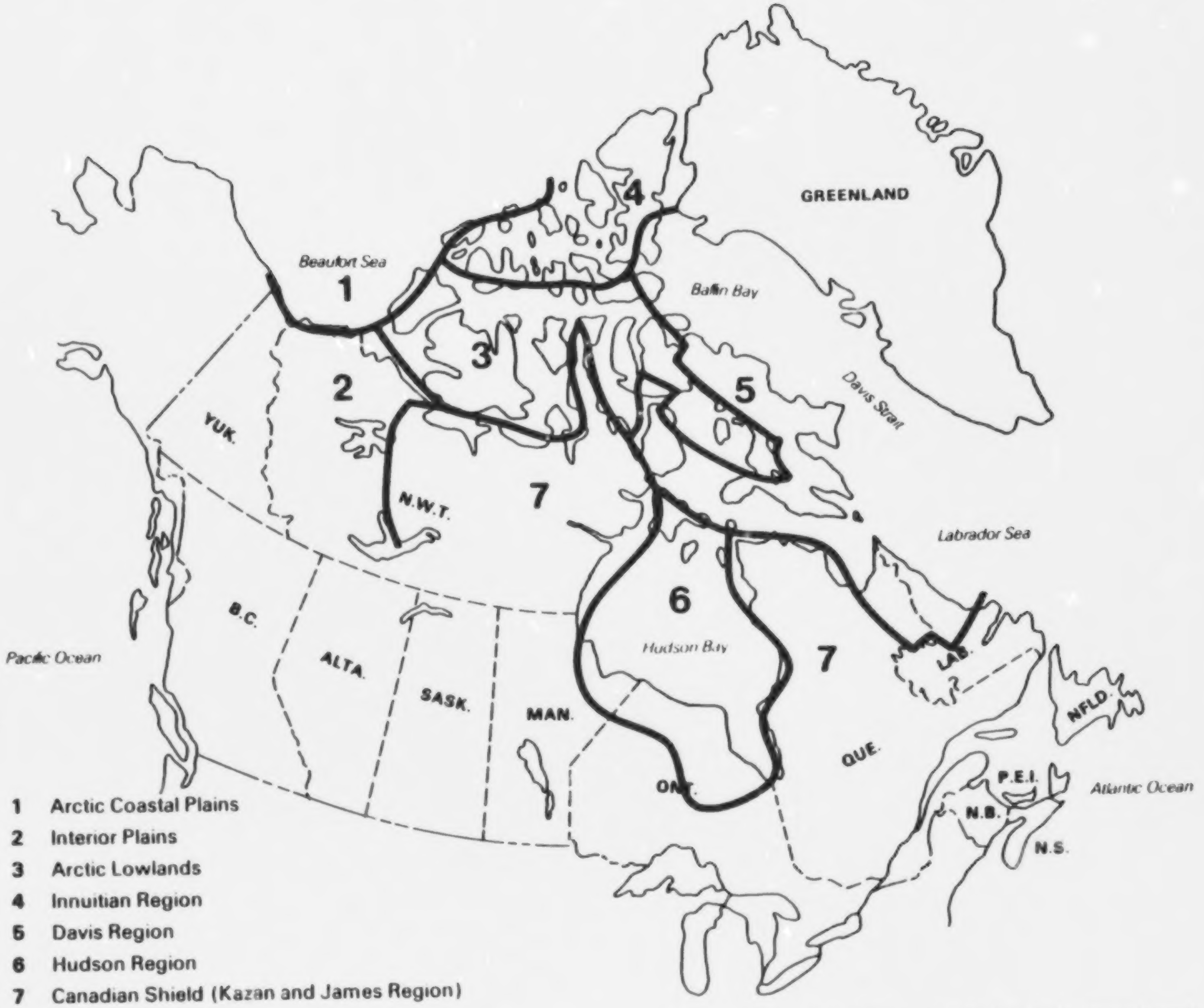

GREENLAND
Beaufort Sea
Baffin Bay
Davis Strait
Labrador Sea
Pacific Ocean
Atlantic Ocean
Hudson Bay
YUK.
N.W.T.
B.C.
ALTA.
SASK.
MAN.
ONT.
QUE.
LAB.
NFLD.
P.E.I.
N.B.
N.S.
1
2
3
4
5
6
7
7
1 Arctic Coastal Plains
2 Interior Plains
3 Arctic Lowlands
4 Innuitian Region
5 Davis Region
6 Hudson Region
7 Canadian Shield (Kazan and James Region)

Figure 4.1 Physigraphic Regions in Northern Canada

Arctic Lowlands (3)

The Arctic Lowlands include parts of Baffin Island, Devon Island, the Boothia Peninsula and Somerset Island, Victoria Island and the east side of Banks Island. The area is generally flat and underlain by Paleozoic and late Proterozoic sedimentary rocks. Steep vertical face coasts occur in the northeast part of the region. On Banks, Victoria and Prince of Wales Islands, the bedrock is covered with extensive moraine deposits.

Innuitian Region (4)

The Innuitian region covers the high Arctic Archipelago with the exception of Devon Island and the southeast shores of Ellesmere Island. The landscape in this region is more rugged than in the surrounding regions. The soil overburden cover is usually shallow and is underlain by sedimentary bedrock which contains occasional intrusions. The shores are gently sloping in the southwest and are very rugged (fjords) in the northeast on Axel-Heiberg and Ellesmere Islands.

Davis Region (5)

The Davis Region includes the east shore of Baffin Island, Ungava Bay and Labrador. This region is part of the Canadian Shield and has limited surficial sediments. Bedrock in this region consists mainly of crystaline Precambrian rocks. The coasts are quite rugged with generally high mountains occurring at a short distance from the sea. Valleys were formed by glaciers flowing into the sea and fjords from a continuation of these glacial valleys.

Hudson Region (6)

The Hudson Region contains the shores of Hudson Bay in the provinces of Manitoba and Ontario. This region is part of the Canadian Shield and is characterized by a belt of raised beaches related to substantial emergence due to geoisostatic rebound. Land surface in the coastal area is gently sloping and the water is shallow. The bedrock is unmetamorphosed formations of the Paleozoic and Proterozoic eras.

Kazan and James Regions (7)

This region is part of the Canadian Shield and covers the Hudson Bay coastline of the Northwest Territories and all the eastern side of Hudson Bay up to and around the Ungava peninsula to include the west coast of Ungava Bay. Bedrock is metamorphic and/or volcanic and the overburden cover is very thin where it exists. The topography is variable, ranging from very rugged to gently rolling. The shores vary from gently sloping to abrupt rock outcrops with no beach.

4.1.2 Genesis of Permafrost

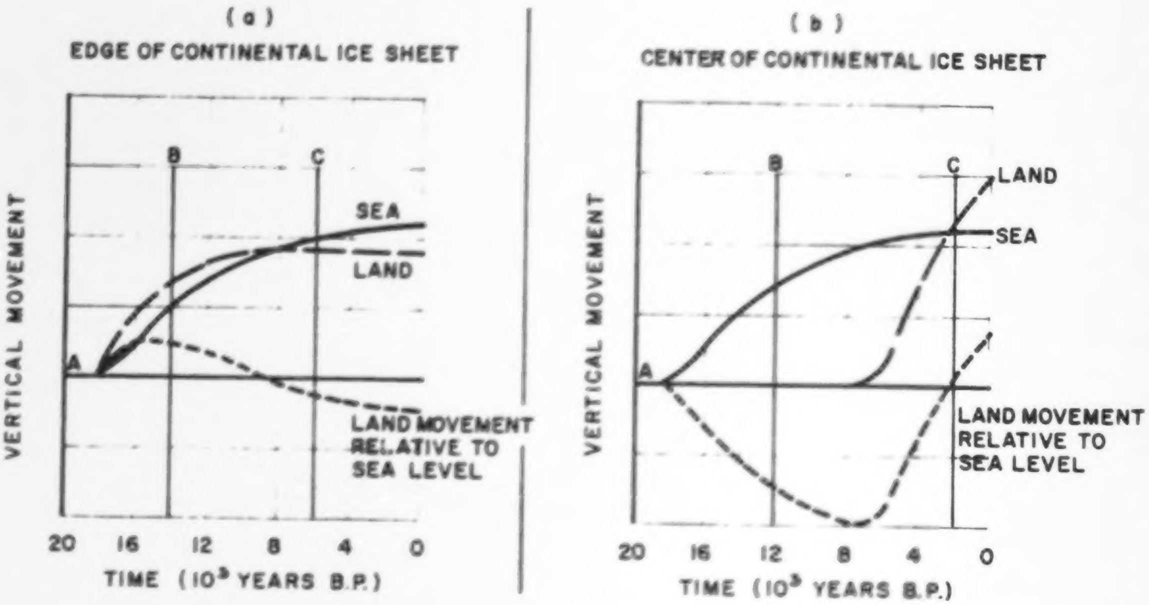
Permafrost is defined solely by the thermal condition of the ground. For a soil or rock to be classified as permafrost its temperature must remain below 0°C for at least two consecutive winters and the intervening summer (Brown and Kupsch 1974 - Vol. 2, Page 177).

Climate is the principal factor affecting the formation and existence of permafrost in the Canadian Arctic. The severe frigid climate has resulted in freezing of soil and rock formations to depths of hundreds of metres. In the Arctic Archipelago, the maximum thickness of permafrost is about 1000 m at inland locations. In the land areas adjacent to the Beaufort Sea, permafrost thickness is typically about 100 m. The extent of permafrost varies with climatic conditions and there is a broad correlation between mean annual air temperature and the distribution of permafrost. The thickness of permafrost varies generally with the amount that mean annual air temperature is below freezing and is limited by heat flow from the interior of the earth. Permafrost distribution and occurrence on land is also affected by other factors such as local terrain conditions, vegetation, drainage, presence of lakes and rivers, snow cover and type of subsurface conditions.

Permafrost in the shoreline area is affected by the adjacent sea due to the significant contrast between the sea temperature and the on land permafrost temperature. This, in combination with sea level changes, geoisostatic rebound and erosional or depositional environments, results in complex permafrost conditions in the shoreline area.

Figure 4.2 illustrates schematically the relationship between sea level rise and geoisostatic rebound. Part (a) of this figure illustrates conditions which would be typical at the edge of the last continental ice sheet where, in recent geologic time, the geoisostatic rebound of the land surface was essentially complete while the sea rise was still in progress. This results in present shoreline conditions where submergence of permafrost has taken place. Part (b) of this figure illustrates conditions at the centre of the last continental ice sheet where geoisostaic rebound of the land surface is still in progress at a rate of about 2 m per 100 years. This results in present shoreline conditions where emergence of the land surface and exposure to prevailing climatic conditions is taking place. Because of the large contrast between arctic air temperatures and sea temperatures, permafrost in coastal areas is not as thick as at inland locations (Taylor et al. 1983 - Vol. 2, Appendix 2).

Permafrost occurring below the sea bottom is defined as subsea permafrost. The presence of subsea permafrost in offshore areas can be explained by four different phenomena:



(B.P. = BEFORE PRESENT)

LEGEND

A AT PEAK OF GLACIATION, PRIOR TO EARTH'S WARMING, SEA AND LAND AT SAME LEVEL.

B AS THE EDGE OF ICE SHEET MELTS, LAND REBOUNDS FASTER THAN SEA LEVEL RISES. PERMAFROST AGGRADES INTO EMERGED LAND.

C LAND RISE IS OVER BUT THE SEA STILL RISES AS THE CENTER OF THE GLACIER MELTS. ONSHORE PERMAFROST IS SUBMERGED.

A AT PEAK OF GLACIATION, PRIOR TO EARTH'S WARMING, SEA AND LAND AT SAME LEVEL.

B SEA LEVEL RISES DUE TO MELTING AT EDGE OF ICE SHEET. AT THE CENTER OF THE SHEET THERE IS STILL CONSIDERABLE LOADING AND THEREFORE NO UPLIFT.

C LAND RISE IN PROGRESS IN DEPRESSED CENTER AREA OF ICE SHEET AND IS CONTINUING TODAY. LAND IS EMERGING AND WILL DO SO FOR SOME TIME. MARINE DEPOSITS ARE EXPOSED IN ONSHORE AREAS.

Figure 4.2 Relationship Between Sea Level Rise and Geoisostatic Rebound

1. Permafrost formed on land and later submerged by the sea rise (see Figure 4.2.a). This is common throughout the western part of the Arctic in areas of lower geoisostatic rebound.
2. Rapid regression of permafrost shoreline due to wave action and ice erosion such as in northern Alaska, Yukon and the Beaufort Sea coast.
3. Aggradation of permafrost into recent sediments in areas of shallow water such as deltaic deposits, where the sea freezes to the bottom.
4. Permafrost in recent deposits due to below zero sea temperatures.

The formation and distribution of subsea permafrost in the arctic is therefore a complex matter, the details of which have not been fully determined at present.

4.1.3 Permafrost Distribution

About 50% of Canada's land surface is underlain by permafrost which can be divided in two main regions: the continuous and discontinuous zones (Brown 1970 - Vol. 2, Page 176). These permafrost zones are illustrated on Figure 4.3. The discontinuous zone which ranges from sporadic occurrence of permafrost in the south to widespread discontinuous permafrost in the north, covers most of the Yukon, the southwestern half of the continental Northwest Territories and the northern areas of all provinces except the lower maritimes. The continuous zone covers the northern Yukon, the north eastern half of the continental Northwest Territories, the western shore of Hudson Bay, the Ungava Peninsula and all of the Arctic Archipelago.

Subsea permafrost has been reported in Ungava Bay and the eastern arctic (Samson and Tordon 1969 - Vol. 2, Page 217), Beaufort Sea (Mackay 1972, Shearer et al. 1971, Judge 1974, Hunter et al. 1976 - Vol. 2, Page 194, Osterkamp and Harrison 1976, 1981 - Vol. 2, Page 209 and 210) and in the Arctic Archipelago (Judge 1974, Holubec and McDonald 1980 -Vol. 2, Page 192). These occurences are directly linked to the last glaciation and the following sea rise. Subsea permafrost is also suspected to occur in unglaciated offshore areas where the isostatic rebound has been small (Judge 1974). Known and suspected areas of subsea permafrost occurences are shown on Figure 4.3.

4.1.4 Characteristics of Subsea Permafrost

In offshore areas, the conventional association of ice with soils at subzero temperatures does not apply. The salt in sea water affects the physical characteristics of the near sea bed permafrost soils. The salt concentration in water prevents nucleation of ice down to temperatures of about -1.8°C, depending on concentration.

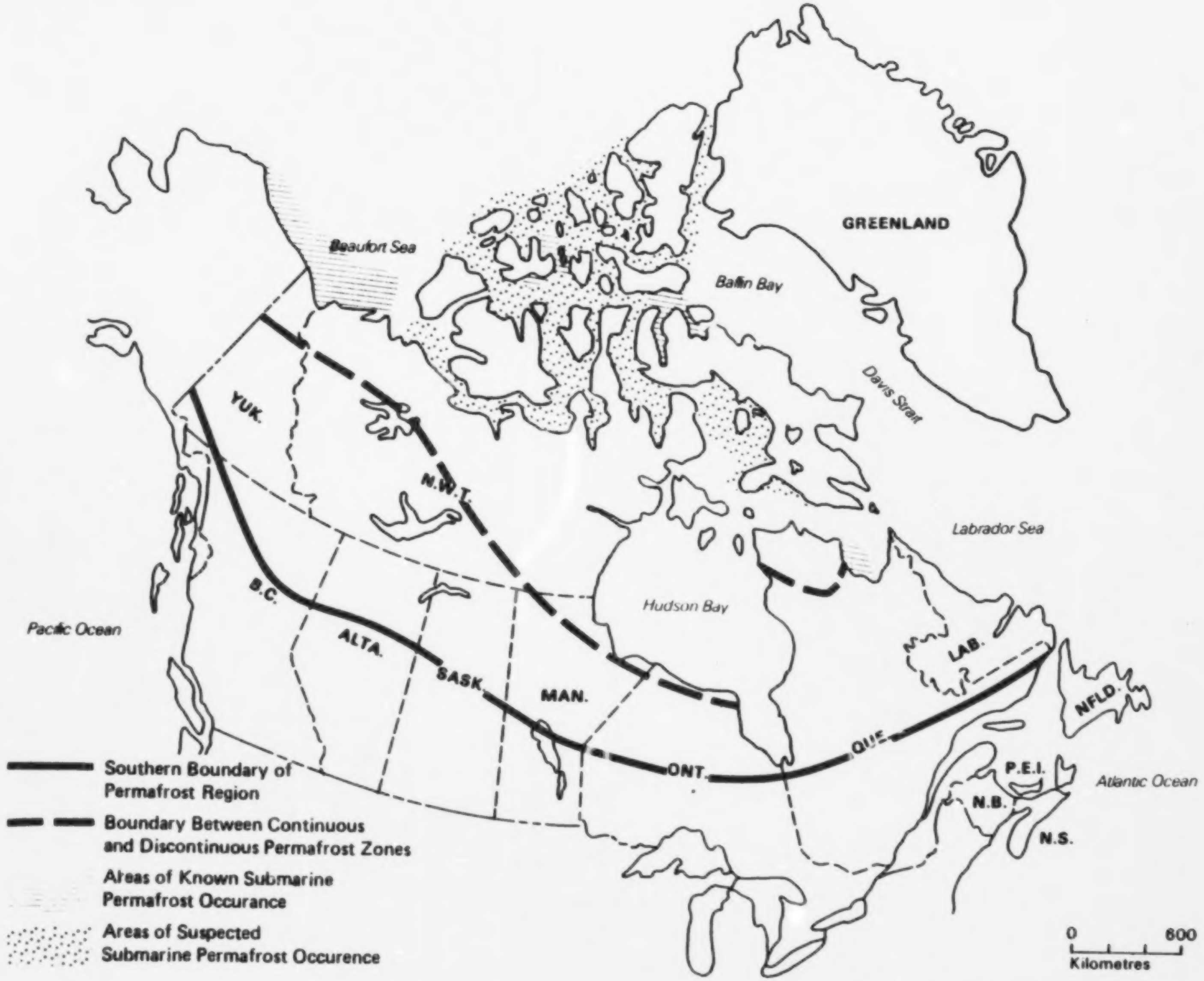

GREENLAND
Beaufort Sea
Baffin Bay
Davis Strait
Labrador Sea
Hudson Bay
Pacific Ocean
Atlantic Ocean
YUK.
N.W.T.
B.C.
ALTA.
SASK.
MAN.
ONT.
QUE.
LAB.
NFLD.
P.E.I.
N.B.
N.S.
Southern Boundary of Permafrost Region
Boundary Between Continuous and Discontinuous Permafrost Zones
Areas of Known Submarine Permafrost Occurance
Areas of Suspected Submarine Permafrost Occurence
0
800
Kilometres

Figure 4.3 Distribution of Permafrost in Canada

Salt in sea water also increases its density so as to minimize thermal reversals and thus subzero temperature water remains at the sea bed year round. The subzero temperatures at sea bed either preserve submerged land formed permafrost or aggrade permafrost into recently deposited sediments. Hence, depending on the geological history of an area, subsea permafrost can occur in various thermal conditions. Where equilibrium conditions are achieved with respect to sea water temperature, subsea permafrost is warm with temperatures between about -1.5°C and 0°C.

Subsea permafrost can occur in an ice-free condition since the salt concentration prevents formation of ice by depressing the pore fluid's freezing temperature. The behaviour of saline, ice-free permafrost is not well understood but some soils have been found to behave the same as their saline, ice-bonded counterparts (Domaschuk et al. 1983 - Vol. 2, Page 187). Saline, ice-free permafrost includes recent sea bed sediments which have settled through salt water.

Subsea permafrost may also contain ice (and be ice-poor or ice-rich) depending on whether or not it contains salt and to what degree it is salt free. Salt-free permafrost with ice originates from pleistocene (glacial) permafrost which was submerged by the sea rise during the last ice retreat. This permafrost is either degrading or at equilibrium. Saline ice rich/poor permafrost has the same origin as its salt-free counterpart with the difference that it exists close enough to the sea bed for salts to have migrated into it. The salt concentration in this permafrost is lower than in the sea water.

In areas where a major river flows into the sea, the brackish water temperature would be warmer than that of salt water and thus the thermal regime in subsea permafrost would be affected. Also, in these areas, fresh or brackish water would occur in the pores of the soil. Where such conditions occur in near shore areas, in conjunction with freezing to the bottom, there would be potential for the formation of ice lenses in frost susceptible soil deposits. Fresh water ice lenses may also be present in permafrost which is submerged by sea rise.

4.1.5 Seismicity

Earthquakes are caused by deformation of the earth's crust due to either radial contraction/expansion of the earth or slow convective motion of the material within the earth. Earthquakes may result in ground motions which are detrimental to structures, may initiate landslides or can cause liquefaction of certain soil deposits.

Liquefaction is a mechanism by which loose, saturated, granular materials lose their strength by pore pressure build-up. It is important to consider the potential for liquefaction of such materials where they occur offshore in a non-frozen condition, even if offshore slopes are relatively flat.

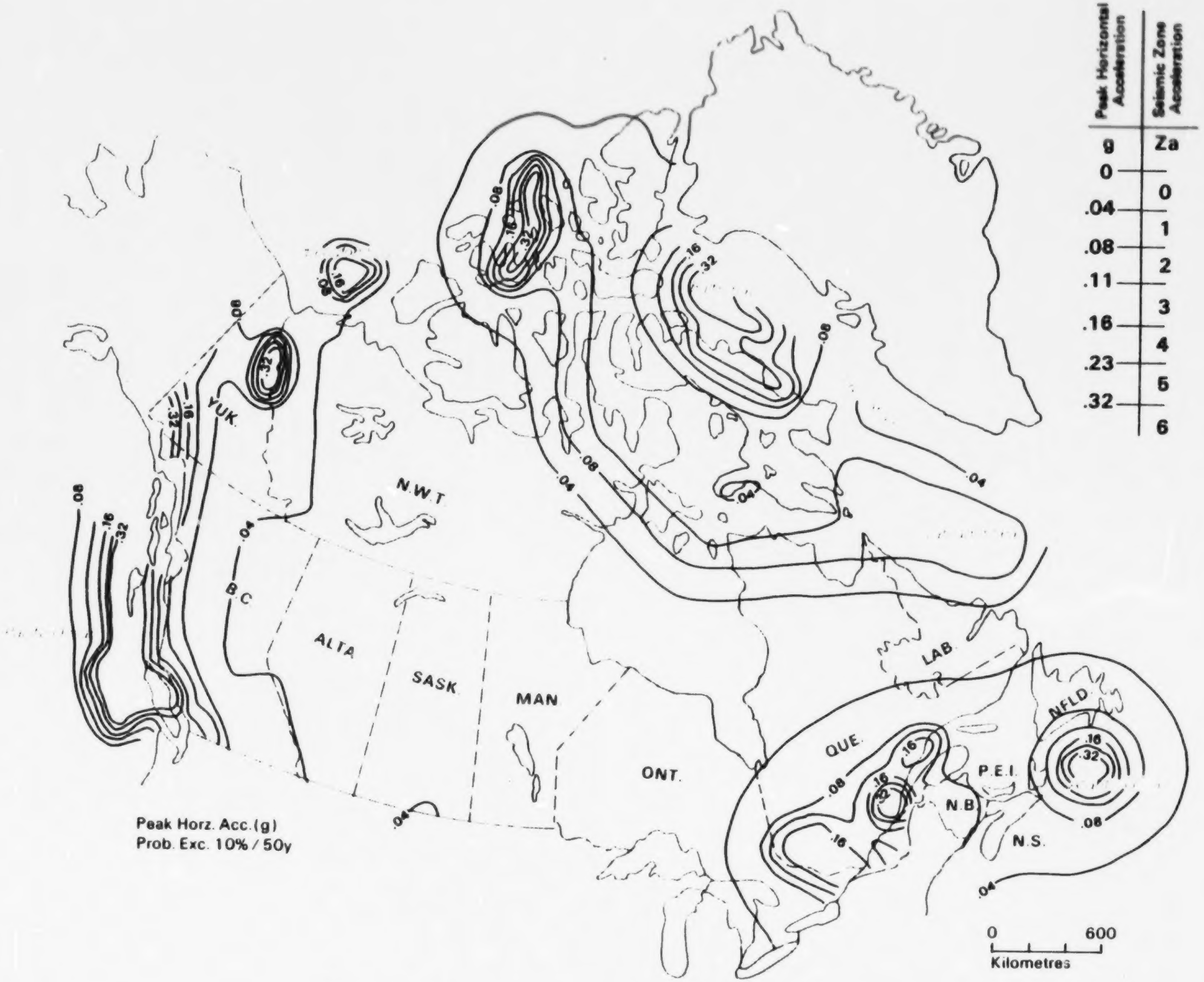

Peak Horizontal Acceleration
g
0
.04
.08
.11
.16
.23
.32
Seismic Zone Acceleration
Za
0
1
2
3
4
5
6
YUK.
N.W.T.
B.C.
ALTA.
SASK.
MAN.
ONT.
QUE.
LAB.
NFLD.
P.E.I.
N.B.
N.S.
.04
.08
.16
.32
Peak Horz. Acc. (g)
Prob. Exc. 10% / 50y
0
600
Kilometres

Figure 4.4 New Acceleration Seismic Zoning Map of Northern Canada (After Heidebrecht et al – 1983)

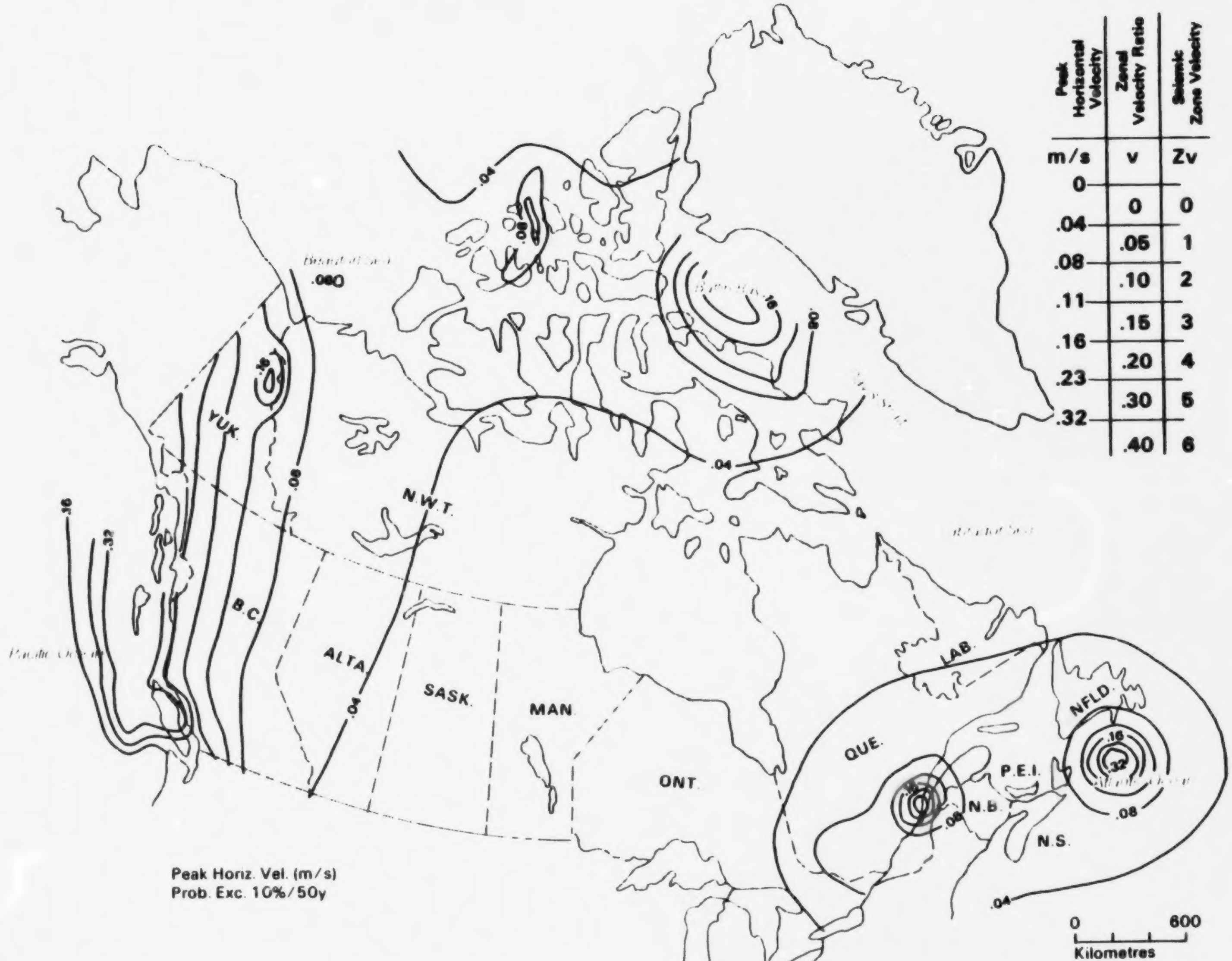

Peak Horizontal Velocity
Zonal Velocity Ratio
Seismic Zone Velocity
m/s
v
Zv
0
.04
.08
.11
.16
.23
.32
0
.05
.10
.15
.20
.30
.40
0
1
2
3
4
5
6
YUK.
N.W.T.
B.C.
ALTA.
SASK.
MAN.
ONT.
QUE.
LAB.
NFLD.
P.E.I.
N.B.
N.S.
.04
.08
.16
.32
.080
Peak Horiz. Vel. (m/s)
Prob. Exc. 10%/50y
0
600
Kilometres

Figure 4.5 New Velocity Seismic Zoning Map of Northern Canada (After Heidebrecht et al)

Tsunamis are long water waves generated in offshore areas by tectonic displacement associated with an earthquake and can cause large "tidal waves" which may affect marine structures. However in arctic waters, there is no record of tsunami occurrence.

New seismic zoning maps were developed for Canada (Heidebrecht et al. 1983 - Vol. 2, Page 191) using historical earthquake records, statistical recurrence curves, geological information and tectonic conditions. These maps (Figures 4.4 and 4.5) have been recommended for inclusion in the 1985 revision of the National Building Code and can be used in the design of most non-critical structures or facilities.

The probability level used for the new zoning maps is expressed as the probability of exceedance of strong ground motion in the average lifetime of a building. A probability level of 10% exceedance in 50 years (return period of one in 475 years) for seismic ground motion was used as being appropriate to the effective design levels provided by the code. In the new seismic zoning maps, the strong seismic motion is defined by peak horizontal acceleration (Figure 4.4) and peak horizontal velocity (Figure 4.5). The seismic zoning maps show a significant potential for seismic activity in the east and northwest parts of the Arctic Archipelego and in the Beaufort Sea area.

Critical structures and facilities in regions of high earthquake risk require a site specific assessment of seismic ground motion.

Site specific data on earthquake risk and ground motion predictions can be obtained at the Pacific Geoscience Centre in Sidney, B.C., or at the Division of Gravity, Geothermics and Geodynamics of the Earth Physics Branch, Earth Sciences, Energy Mines and Resources, Ottawa.

4.2 Site Studies

4.2.1 General Scope of Site Studies

The scope of a site study for an arctic marine structure will depend on the type, size and location of the structure to be built. The importance of the structure and availability of construction materials will also influence the scope of a site study.

Depending on the size and constraints of the project, site studies can be done in one or several of the following progressive phases depending on time and budgetary considerations:

- Feasibility study
- Preliminary site evaluation
- Final site investigation

These phases of site studies as well as data sources are summarized on Figure 4.6.

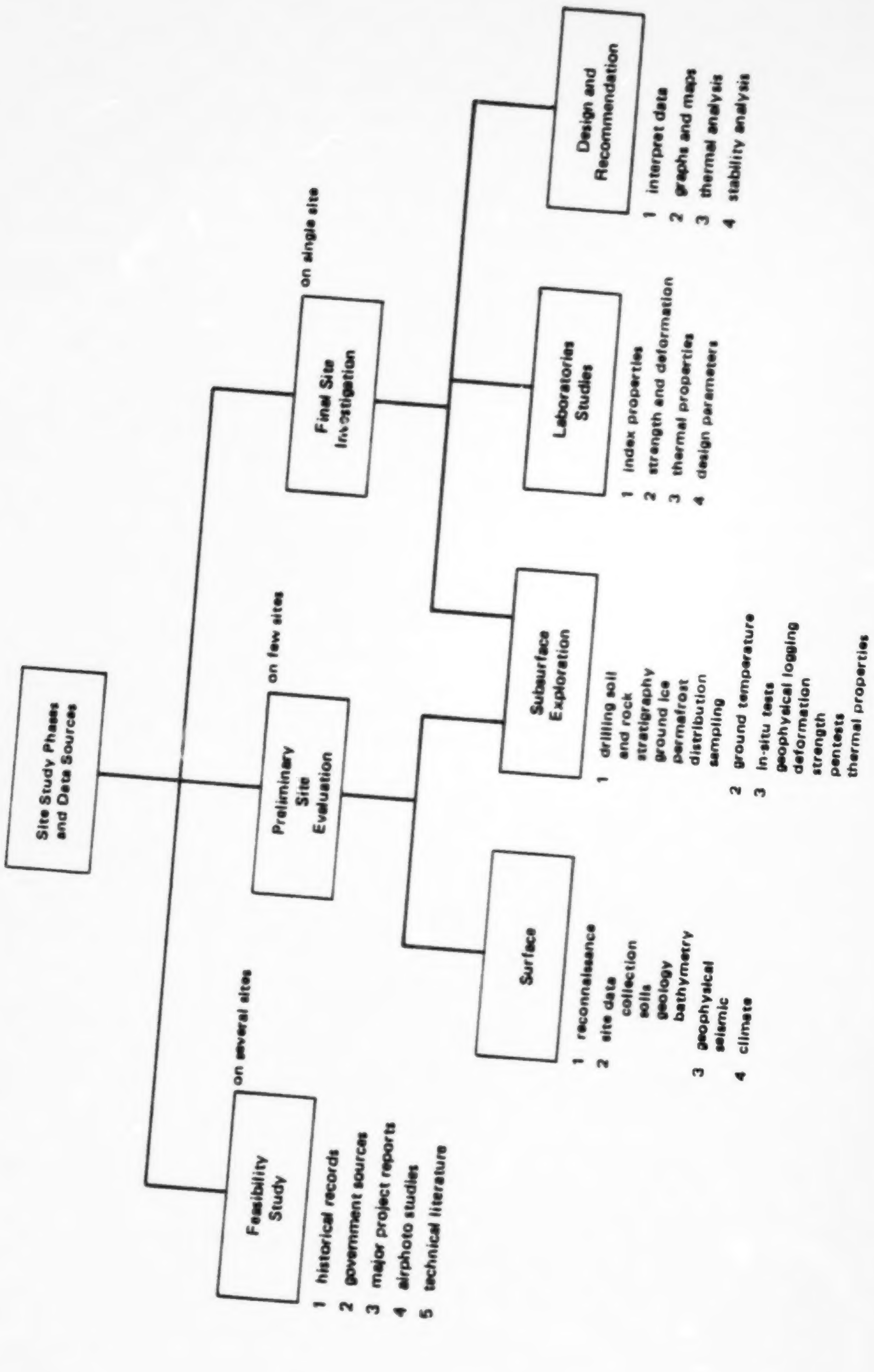

Site Study Phases and Data Sources
Feasibility Study
on several sites
1 historical records
2 government sources
3 major project reports
4 airphoto studies
5 technical literature
Preliminary Site Evaluation
on few sites
Surface
1 reconnaissance
2 site data collection
soils
geology
bathymetry
3 geophysical seismic
4 climate
Subsurface Exploration
1 drilling soil and rock
stratigraphy
ground ice
permafrost distribution
sampling
2 ground temperature
3 in-situ tests
geophysical logging
deformation
strength
pentests
thermal properties
Final Site Investigation
on single site
Laboratories Studies
1 index properties
2 strength and deformation
3 thermal properties
4 design parameters
Design and Recommendation
1 interpret data
2 graphs and maps
3 thermal analysis
4 stability analysis

Figure 4.6 Site Study Phases and Data Sources

Feasibility Study

Normally, in the feasibility study, market and socio-economic considerations dictate a choice of sites on which the geotechnical engineer provides a preliminary assessment using air photographs, geological maps or other information available from government agencies. In some instances, the choice may be limited to a single site. The feasibility study may or may not entail site visits.

The information sought during the feasibility study includes bathymetry, surficial geology, bedrock geology, seismicity and subsea soil conditions. Depending on the amount of available data, a conceptual design of the proposed marine structure can be made.

Preliminary Site Evaluation

Before proceeding with the preliminary design of the marine structure at an established location, it is customary to conduct a preliminary site evaluation which includes coarse-grid bathymetry, onshore geological reconnaissance, evaluation of ice conditions and a subsurface exploration programme which can be done with light portable equipment. The information gathered from this programme is used to more accurately locate the structure on a single site or to locate a site from several alternatives, and to carry out preliminary foundation design. The preliminary design of the facilities and the preliminary geotechnical information will allow proper planning for the final site investigation.

Final Site Investigation

The final site investigation programme is carried out to obtain detailed information on subsurface conditions and engineering design parameters required for the final design of the marine structure and supporting facilities. A discussion of construction methodology is given in the geotechnical investigation report. The final site investigation usually includes:

- Subsurface Exploration:
  - drilling and sampling
  - geophysical surveys
  - in-situ testing
  - ground temperature measurements
- Laboratory Testing
- Design Considerations:
  - stability analyses
  - bearing capacity analyses
  - settlement analyses
  - soil/structure interaction analyses
  - thermal analyses

The above aspects of a final site investigation are discussed in later sections.

4.2.2 Logistical Considerations for Field Work

In planning and executing a subsurface exploration programme in the arctic, one must be prepared to operate in a remote area and under potentially harsh climatic conditions.

The efficiency of any field programme is dependent on the arctic experience of the field manager and his staff and more so on carefully planned logistics. Site exploration work requires well executed logistical co-ordination and it is adviseable that the control of all logistics be placed under the responsibility of one organization.

Offshore site investigations are normally conducted in early spring for near shore structures where the work can be conducted from ice or during the summer period from marine vessels after the ice has melted. For work from ice, the months of April, May and part of June are normally suitable while offshore work from marine vessels is conducted in July, August and possibly into September.

4.2.3 Subsurface Exploration

4.2.3.1 General Scope of Subsurface Exploration

In general, the scope of a subsurface exploration programme is to determine the lithology of soils and rocks, existence of permafrost, the form and distribution of ground ice, groundwater conditions, depth of active layer, presence of taliks (unfrozen layers) and ground thermal regime. Site exploration should also include bathymetric surveys to define sea bottom configuration and major discontinuities such as ice scour tracks and "pingo-like" features.

The extent of subsurface exploration depends on the size of the proposed structure and its interaction with the surrounding soils. The minimum depth of borings and soundings is generally taken as the width of the proposed structure unless a competent bearing stratum or sound rock is encountered at a shallower depth. Borings in thawing permafrost should be carried out to a depth of at least 3 m below the maximum estimated depth of thaw penetration. When piles or sheet piles are contemplated, the exploration depth should extend at least 3 m below the bottom of the foundation.

Comprehensive exploration programmes are conducted to obtain undisturbed samples of frozen and unfrozen soils (including saline soils) to determine the laboratory frost heave characteristics, thaw-settlement properties, strength and creep properties and thermal properties (unfrozen water content, conductivity and heat capacity). In-situ testing may be carried out in test holes and special instrumentation may be installed and left in place. Large scale tests such as trenching, blasting, pile load tests and trial embankments may be carried out to obtain practical data for foundation design and to establish optimum construction methods.

4.2.3.2 Drilling and Sampling Permafrost

Onshore permafrost samples can be secured from natural exposures, hand borings, test pits and core drilling. The first three methods are generally applicable for shallow depths (3 m or less) where the permafrost is relatively warm (0 to -4°C). These techniques have been thoroughly reviewed (Johnston 1981 - Vol. 2, Page 196).

In cold permafrost at greater depth and in offshore permafrost, core drilling is required. Core drilling onshore has also been reviewed (Johnston 1981). This section will only discuss offshore drilling and sampling methods for subsea permafrost.

Test holes in shallow (less than 30 m of water) offshore areas can be drilled either from a vessel or from the surface of the ice during the winter or spring. Because of the warm nature of subsea permafrost, the permafrost can readily be thawed during drilling and therefore great care is required in the drilling procedure. Rotary drilling with a drilling fluid which can be maintained below 0°C is commonly used. Drilling fluids which have been used are diesel fuel, sodium chloride and calcium chloride brine solutions and antifreeze (alcohol or glycol). To maintain the drilling fluid below 0°C chillers may be needed. In selection of drilling fluids, due consideration should be given to their effect on the environment. Vibratory (resonant) drills have also been used to obtain mechanically disturbed but stratigraphically intact seabed cores (Huck and Hull 1971 - Vol. 2, Page 193; Hayley 1979 - Vol. 2, Page 190). A variety of light weight drilling equipment has been used in areas of landfast ice and very shallow offshore areas (Osterkamp and Harrison 1976, 1981; Judge et al. 1976) with different degrees of success. These tools are usually suited for preliminary site investigations rather than for final detailed drilling.

The principles of sampling frozen materials offshore are similar to those of diamond drilling in rock. Because of the erodible or friable nature of the material being cored, triple tube, swivel head core barrels giving cores at least 50 mm in diameter are generally used. The core barrel bits can be set with either diamond or hard metal insert type teeth. The bits should be of the bottom discharge type to minimize washing action on the core.

Unfrozen soils and ice-free permafrost soils are commonly sampled with standard split barrel samplers and thin walled tubes (pushed in with piston or pushed manually).

When samples are brought back to surface, they are visually inspected and classified according to the presence of ice (Pihlainen and

Johnston 1963 - Vol. 2, Appendix 2). Permafrost samples are normally photographed and carefully protected and stored to preserve their undisturbed frozen state for laboratory testing. The storage and shipping temperature must be as close as possible to the in-situ temperature. Routine testing to establish index properties and ice content is usually carried out in a portable site laboratory.

4.2.3.3 Geophysical Surveys

Geophysical survey methods can supplement drilling observations and provide less expensive means of expanding the subsurface data. Geophysical techniques and their application to problem solving in permafrost regions have been reviewed (Scott et al. 1979 - Vol. 2, Page 218). The authors conclude that the appropriate selection and application of a geophysical method or combination of methods for permafrost studies can be difficult even with knowledge of the many available systems. Geophysical survey methods are not applicable to every problem, hence a rational approach to the selection of geophysical methods for solving geotechnical problems must be taken.

4.2.3.4 In-situ Testing

In-situ testing is often used to obtain engineering soil parameters and minimize problems associated with scale effect and sample disturbances. Identification of in-situ testing techniques used in offshore holes is given below.

Pressuremeters have been used successfully in test holes and in self-boring units in the Beaufort Sea. This equipment requires considerable experience in conducting the test and interpreting the data. Pressuremeter tests have been used on land to study the strength and deformation properties of frozen soils (Ladanyi and Johnston 1973 - Vol. 2, Page 198; Rowley et al. 1975 - Vol. 2, Page 216).

In the unfrozen soil strata the common type of in-situ tests are vane shear strength tests in cohesive soils, static cone penetration test (CPT) and permeability tests. The CPT has experienced considerable increase in use for foundation investigations because it is rigid, economical and can simultaneously measure pore water pressure and soil temperature (J. DeRuiter 1981 - Vol. 2, Appendix 2).

Static penetrometers as well as electric and acoustic piezopenetrometers have been used in the Beaufort Sea to determine engineering properties and distribution of material types, including distribution of ice bonded sediments (Blouin et al. 1979 - Vol. 2, Page 175).

4.2.3.5 In-situ Ground Temperature Measurements

Various types of temperature sensors, including mercury themometers, thermocouples, thermistors and diodes, are available for the measurement of ground temperatures. Thermocouples and thermistors are the most widely used for engineering field investigations. Since temperatures are usually required at several depths at one location, multiconductor cables or several cables containing sensors at the desired intervals are inserted after drilling a test hole. The test hole should be carefully backfilled, particularly near the ground surface, to prevent percolation of surface water down the hole. Recently, techniques have been developed to allow one point measurement of temperatures with a probe which can be moved up and down a cased hole in still air or fluid. This technique can be used only before abandonment in offshore holes. In-situ temperature measurement techniques have been reviewed (Johnston 1981 - Vol. 2, Page 196, and Judge 1972 - Vol. 2, Appendix 2).

4.2.4 Laboratory Testing of Frozen, Freezing and Thawing Soils

Laboratory testing of soil and rock specimens is conducted for classifying the material and obtaining engineering properties (strength, compressibility, creep, etc.) needed for the design of earth structures and foundations. Laboratory test results are also used to assess the suitability of borrow materials and to define potential construction difficulties.

Laboratory tests routinely carried out on permafrost soils include density and water content tests. These index properties are useful in assessing the thaw settlement and thermal properties of frozen soils. Other index tests carried out on frozen and unfrozen samples include particle size distribution, Atterberg limits and specific gravity.

Unfrozen moisture content in permafrost samples can be measured using a number of techniques (Anderson and Morgenstern 1973 - Vol. 2, Page 172) but recently, a new technique, time domain reflectometry, was used with satisfactory results in frozen non-saline soils (Patterson and Smith 1981 - Vol. 2, Page 211). However in saline permafrost there are doubts that the method is effective because of the dielectric properties of salt water.

For the determination of engineering properties needed in design, test methods routinely used in temperate soil and rock mechanics must be modified to include provisions for accurate control of test temperature and long term testing of frozen materials.

Strength and deformation properties of frozen soils and rocks vary greatly with temperature, moisture (ice) content and duration of loading. Laboratory testing programmes must realistically model site loading conditions to produce the most relevant geotechnical design parameters.

Tests easily carried out on frozen soils include simple consolidation (without temperature or pore pressure dissipation monitoring) and unconfined compression. The first is to assess total potential settlement upon thawing and the second gives a qualitative strength measurement. These tests are only used for simple design problems. When designing major structures in sensitive warm permafrost more specialized tests with deformation rate and temperature control using specially designed equipment and facilities are carried out.

The testing of freezing soils is carried out in "frost cells". Although no uniformity yet exists in testing equipment and methods, certain basic features are common to all laboratory equipment of this type. Mageau and Sherman, (1983 - Vol. 2, Page 202) have reviewed all equipment used by other researchers and proposed a frost cell design and operating procedure.

Testing of thawing soils is carried out in specially designed oedometers with a heating plate and pore pressure measurement sensor on top and temperature sensors on the side. Such an apparatus allows study of the entire thaw-consolidation process (Smith and Morgenstern 1973; Nixon and Morgenstern 1974 - Vol. 2, Page 205).

The Permafrost Subcommittee of the Associate Committee on Geotechnical Research, National Research Council of Canada, (Vol. 2, Appendix 1) is preparing a set of procedures and test methods for the laboratory testing of permafrost. This manual will provide a first step towards the establishment of standard testing practice to improve the quality, comparability and usefulness of laboratory test data.

4.3 Foundation Design Considerations

4.3.1 General

Geotechnical design methods used in southern regions for shoreline structures are also used in the arctic with the following additional considerations: presence of permafrost, changes of thermal regime, large lateral ice loading and ice scour of earth/rock berms. Implicit with all geotechnical design methods is appropriate consideration of seismicity in respect to potential liquefaction of soils and seismic loading conditions.

Foundation design in arctic shoreline and offshore areas will be greatly dependent on the following foundation soil considerations:

Unfrozen Soils

If investigations show that unfrozen soils are present under the sea bed and that future construction will not produce freezing, established southern design approaches can be used.

Thermal Changes

The construction of a structure on the sea bed can produce either the thawing of permafrost with resultant settlement and strength reduction or the freezing of unfrozen soil with resultant frost heave. Therefore the potential of ground thermal regime changes and their effect on the proposed structure have to be considered.

Thaw-Stable or Non Ice Bonded Permafrost

This type of permafrost provides a competent foundation for marine structures and earthworks as long as the cold regime is maintained. In most cases adequate foundation support is maintained when this type of permafrost thaws.

Ice-Rich Permafrost and Massive Ground Ice

This type of terrain is the most adverse for foundations. In the short term, ice-rich soils provide excellent support. In the long term, ice-rich soils and massive ground ice could be a problem due to creep movement under sustained loading. Such creep movements can adversely affect a marine structure even when thawing of the permafrost does not occur. Therefore, structures on ice-rich soil or massive ground ice are designed for a limiting creep occuring during the life of the structure. Creep is a function of temperature, stress level, and to a lesser extent soil type and ice content. Thawing of ice-rich permafrost and massive ground ice would of course result in unacceptable settlement.

An example of large settlement due to thawing of ice occurred at the Nanisinik Mine in the high Arctic (de Ruiter, 1984). At this site the mill building, constructed on bedrock, showed signs of subsidence several years after start-up of the mill. It was established that settlement of the structure resulted from partial melting of an ice lens some 1 to 1.5 m in thickness and located about 10 m below bedrock surface. Remedial measures to arrest settlement and save the mill consisted of mining out the ice and constructing concsrete pillars.

4.3.2 Design Approach

Arctic marine structures may involve various combinations of the factors outlined in Section 4.3.1. Therefore, geotechnical design of an arctic marine structure requires a design approach that will take into account all of the relevant factors. A design approach (modified after Johnston 1981) is illustrated on Figure 4.7.

As shown, the design approach will firstly depend on the presence or absence of permafrost. If permafrost does not exist at the location of the structure, and if freezing is not anticipated during the life of the structure, design methods for the temperate zone may be used. If permafrost exists, it can be either as thaw-stable or thaw-unstable. The design approach for thaw-stable conditions is the same as for temperate zones as no detrimental effects result from thawing of the ground. Thaw-unstable conditions require special design approaches as discussed below.

The interaction of a structure with permafrost may lead to warming of the ground and eventually to complete thaw, thus resulting in severe foundation deformation. The presence of ice-rich permafrost and massive ice lenses can result in large deformations as they are weaker and creep faster at higher temperature. These material involve a significant reduction in foundation support upon thaw due to the accumulation of excess pore water unable to escape through the soil matrix. Such conditions, which frequently occur in fine grained soil and sedimentary rock deposits, are called thaw-unstable and require special design approaches. Generally, the design approaches fall into two categories, the passive and the active methods.

In the passive method, the ground thermal regime is maintained by artificial cooling methods and ground insulation. This approach should only be used where the permafrost is well established and is not in a marginal condition.

In the active method, two avenues are possible. First, the changes in ground thermal regime conditions caused by construction and operation or by natural permafrost degradation are accepted and accounted for in the design. This is the most common design approach in offshore foundation design and is valid for any type of structure as long as they can accept the deformation imposed on them. Second, unfavourable foundation materials can be modified prior to construction. This design approach can only be used with difficulty and is seldom economical.

4.3.3 Foundation Analyses

Shoreline structures in the arctic are subjected to exceptional ice loading as well as other loads from earth pressures, seismic effects, ship docking and so forth as outlined in Chapter 8. The stability and performance of foundations for such structures have to be evaluated and analysed for the following aspects:

- bearing capacity of supporting strata
- slope stability if structure founded on sloping sea bed, especially if an approach earth fill is involved
- overturning and foundation edge pressure under lateral loading
- sliding at structure/soil interface or shear through foundation soil
- lateral and vertical capacity of piles
- settlement due to compression/consolidation of unfrozen or partially frozen soils

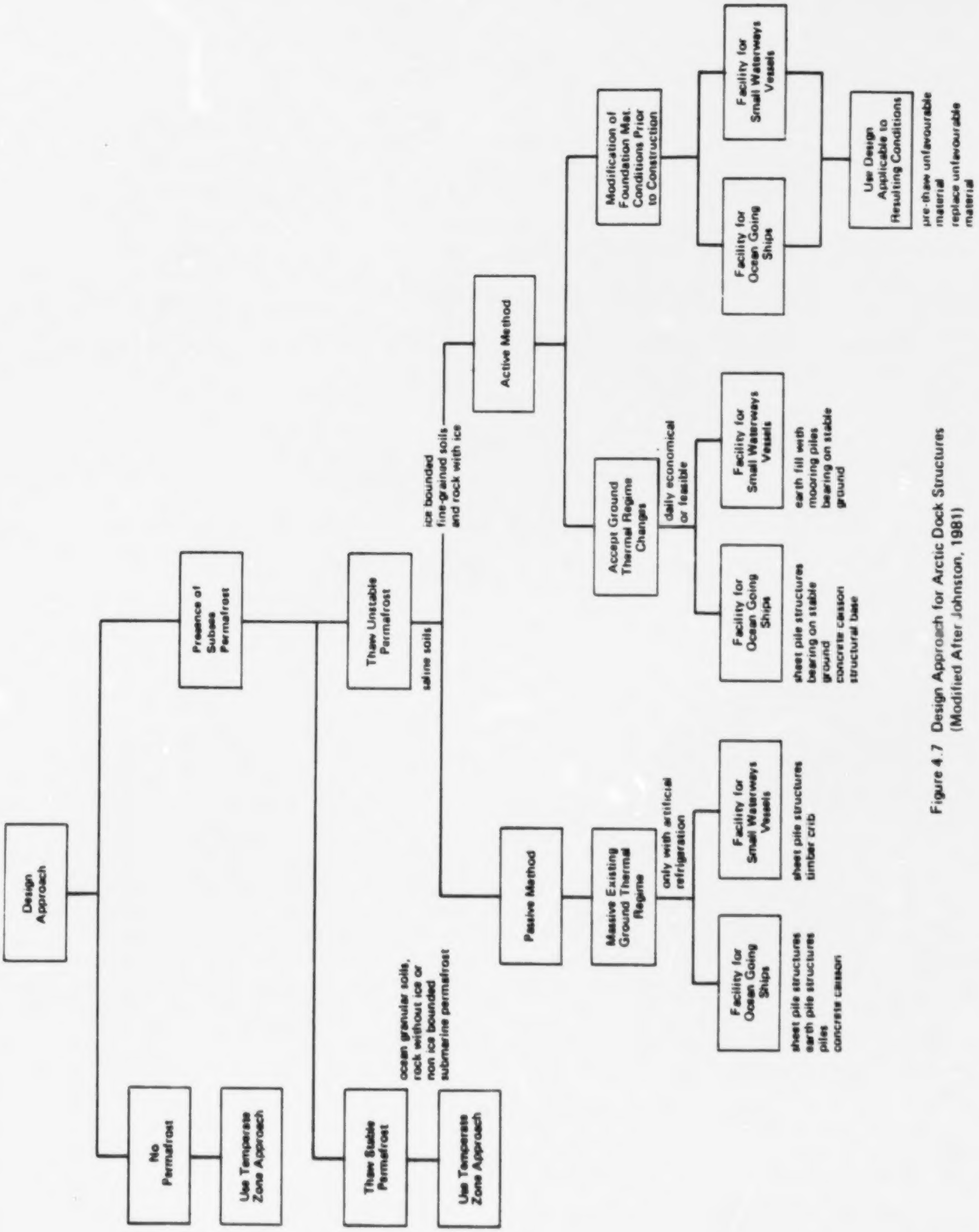

Design Approach
No Permafrost
Use Temperate Zone Approach
Presence of Subsea Permafrost
Thaw Stable Permafrost
Use Temperate Zone Approach
ocean granular soils, rock without ice or non ice bounded submarine permafrost
Thaw Unstable Permafrost
saline soils
ice bounded fine-grained soils and rock with ice
Passive Method
Massive Existing Ground Thermal Regime
only with artificial refrigeration
Facility for Ocean Going Ships
sheet pile structures
earth pile structures
piles
concrete caisson
Facility for Small Waterways Vessels
sheet pile structures
timber crib
Active Method
Accept Ground Thermal Regime Changes
daily economical or feasible
Facility for Ocean Going Ships
sheet pile structures bearing on stable ground
concrete caisson structural base
Facility for Small Waterways Vessels
earth fill with mooring piles bearing on stable ground
Modification of Foundation Mat. Conditions Prior to Construction
Facility for Ocean Going Ships
Facility for Small Waterways Vessels
Use Design Applicable to Resulting Conditions
pre-thaw unfavourable material
replace unfavourable material

Figure 4.7 Design Approach for Arctic Dock Structures (Modified After Johnston, 1981)

- settlement due to thaw consolidation of permafrost or frost heave due to ice formation in non frozen seabed soils

- creep of frozen soil or ice

- seismic effects on slope stability, lateral loads and bearing capacity

- liquefaction potential of foundation soils

- vibratory loads from pumps and other such equipment

- the presence of ancillary systems such as oil pipelines.

Methods of foundation analyses with respect to the above aspects are generally consistent with techniques used in temperate climates. However, selection of geotechnical parameters for foundation analyses in permafrost conditions requires considerable experience in combination with comprehensive field data and laboratory test results.

4.3.4 Geotechnical Consideration for Specific Structures

The following are brief comments with respect to geotechnical design considerations for specific types of marine structures in the arctic. In addition to the specifics discussed below, design of all marine structures should take into consideration shoreline erosion processes and the influence of construction on land as it affects the thermal stability of permafrost at the structure in the shoreline area.

Timber Cribs

Timber cribs have been used as low cost docks for shallow draft vessels. They are constructed in shallow water and are normally supported on one or more sides (shore side by granular fill). Timber cribs can sustain large vertical and horizontal movements and can withstand large horizontal forces from the sea direction because of resistance of granular fill behind the cribs. Cribs derive their support in part by shear resistance of the mass of granular fill within them.

The only unfavorable foundation condition for cribs is soft clay which causes excessive settlement and may result in bearing capacity failure.

Caissons

Steel or concrete caissons may be constructed in a protected area in the arctic or, in the south, towed to the desired site and sunk on a prepared granular pad. The pad can be constructed by either levelling the existing sea bed (if granular) or by placing a granular mat directly on the existing or dredged sea bed. Caissons have to be analyzed for bearing capacity, settlement, lateral load and all other aspects mentioned in Section 4.3.2. Caissons must provide resistance to large lateral ice loads. To increase lateral resistance, rock fill abutments (on the shore side) can be provided or piles can be used to anchor the structure into the subsoils.

Piles

Piled offshore structures have been considered in conceptual designs but have not yet been used in the Canadian Arctic. The large cross sectional area of piles required to resist lateral ice forces makes it difficult to install piles by driving or by predrilling to the depth necessary to develop the lateral soil resistance.

It may be possible to drive heavy section H-piles in arctic offshore soil being either ice-free or ice-bonded. The ice-bonded permafrost is normally above -1.5°C, which is similar to land based discontinuous permafrost where H-piles have been successfully driven for years in the past.

Sheet Piles

Sheet piles have been used extensively in the arctic offshore areas for construction of circular cells and longitudinal wall enclosures. Sheet piled structures can resist large lateral loads by their large mass anchored into the sea bed. The main geotechnical concerns are: a) preparation of the sea bed, b) driving of sheet piles into permafrost, especially if it is frozen granular material, and c) availability of good granular cell fill. The shear strength of granular fill within the cells provides significant resistance to lateral forces and to excessive deformation. If this granular fill freezes, resistance to lateral forces is greatly increased. It is difficult to predict the extent to which freezing will take place. In this regard, freezing of granular fill below water level and seasonal ice levels would not be expected. However, freezing of granular fill above water level and to some extent within the tidal zone, if the latter is significant, would be expected in areas where the average annual air temperature is below -1°C. Growth of permafrost into steel sheet pile cells from land side fills and from underlying permafrost is also a consideration. Thermal monitoring of actual steel sheet pile cells is considered to be important for adequate comprehension of the mechanisms involved.

4.4 Earth Works

4.4.1 General

Earth works for marine facilities may involve the following: fill for onshore facilities, quarries and borrow pits, offshore excavation and offshore earth structures (causeways, sea bed granular pads and earth cells).

One major distinction between onshore and offshore excavation is, besides the presence of water, the warmer permafrost temperatures in the offshore which makes excavation much easier.

On land the temperature of soils near the ground surface varies seasonally with air temperature. At a depth of about 10 to 15 m ground temperature does not vary seasonally and is generally several degrees warmer than mean annual air temperature. In the high Arctic the steady ground temperatures at about 10 to 15 m depth, may in land areas, be -10 to -17°C.

In offshore areas the sea bed soils experience warmer temperatures, generally being warmer than -1.5°C where equilibrium conditions have been reached. The surface of the sea bed, except in shallow water where the ice freezes to the bottom during the winter, is unfrozen because of the presence of saline water. This unfrozen layer may be underlain by either unfrozen material or zones of subsea permafrost.

The warm subsea permafrost is more easily penetrated and excavated, but can also be more easily disturbed by new construction, in comparison to colder permafrost. Therefore, the effect of earth fills or excavation on the thermal stability of subsea permafrost requires careful consideration in design.

4.4.2 Borrow Material

Borrow material in the arctic is normally restricted to granular materials such as sands, gravels and crushed rock from quarries. These materials can be readily excavated, placed and compacted when of low moisture content (approximately less than 2%). Fine grained materials such as silts and clays are generally difficult to excavate and compact when frozen and are difficult or impossible to place and compact when thawed because of their normally high moisture content.

The availability of sands and gravels is difficult to summarize because the Canadian north contains several physiographic regions which have been affected by different degrees of glaciation and marine inundation. Generally these processes lead to the formation of the following granular deposits:

Fluvial - riverbed, terrace and delta deposits
Glacio Fluvial - eskers and kames
Inundation - raised beaches, bars, hookes, etc.

The following table summarizes the most common types of granular resources prevalent in each physiographic region.

Physiographic Region	Type of Granular Deposit
Arctic Coastal Plains (1)	Fluvial
Interior Plains (2)	Fluvial
Arctic Lowlands (3) (northern most part)	Fluvial and Inundation
Innuitian (4)	Fluvial and Inundation
Davis (5)	Fluvial and Inundation
Hudson (6)	Fluvial, Glacio-Fluvial, Inundation
Kazan & James (7)	Fluvial, Glacio-Fuuvial, Inundation

Table 4.1 Granular Deposits Prevalent in Northern Canadian Physiographic Regions

Granular deposits which were previously submerged or which were formed in a marine environment may have a significant salt content. The presence of saline borrow materials should therefore be checked and the implications of their use for concrete aggregate and fill should be evaluated.

Another source of granular material is from sea bed deposits which have been deposited from land by fluvial or glaciofluvial action prior to the sea rise. Most of the known offshore granular materials are ice-free and therefore readily excavated by conventional dredging techniques.

Bedrock can also be used as a granular source. The Canadian Arctic encompasses numerous geological provinces with bedrock varying from undesirable sedimentary rocks to competent metamorphic and igneous rocks. In the establishment of a rock quarry it is necessary to find a readily accessible bedrock outcrop which will produce a structurally and weathering stable granular material.

4.4.3 Excavation

Onshore

The extent to which excavation of soil onshore can be carried out is greatly dependent on time of year, depth of deposit and ice/water content. A review of various methods of excavating frozen ground is given by Johnston (1981 - Vol. 2, Page 196). The following general comments can be made:

- Excavation of frozen fine grained soil using mechanical equipment is difficult to impossible.

- Frozen fine grained soil can be broken by blasting. This has been done for small excavations.

- Frozen fine grained soil and ice bonded sands and gravels can be excavated by following a method of thawing and farming during the summer months. The type of soil and the amount of water in the soil after thawing governs the 'mud' condition within the excavation. Silty sands, sands and gravel can be dozed into ridges and drained while drying of clayey soils is more difficult.

- Dry frozen clean sands and gravels can be excavated and lumps broken even during the coldest part of winter. However densities normally specified in temperate climate cannot generally be achieved during freezing temperatures.

Offshore

Offshore excavation may be required for several reasons, such as, structure pad levelling, increasing water depth at dock and pipe burial. Presently there is limited information on the excavation of subsea permafrost.

Sea bed soils in the high arctic are submerged by sea water colder than 0°C and normally not below -1.8°C. In this temperature range, soil conditions and excavation of soils can be summarized as follows:

- Clays silts, sands and gravels are normally ice free and their properties and behaviour are similar to that occurring in temperate climates, therefore experience gained there is applicable.

- Fine silts and clays from glacial periods may or may not contain excess ice. Generally speaking these materials are stiffer than thawed soils but excavation may be possible with heavy equipment.

- Subsea bedrock - no information is available on this subject. However since bedrock at shallow depths develops its strength from internal cohesion, it is believed that the added cohesion due to ice will marginally increase the strength of the rock.

4.4.4 Compaction

Arctic marine structures usually involve fills which require compaction. Compaction of non frozen fills in above freezing temperatures is similar to procedures used in temperate zones. However the use of frozen fill materials and/or fill placement in below freezing temperatures requires special consideration.

A comprehensive study of cold regions engineered earthworks has recently been carried out (Transportation Development Centre 1983 - Vol. 2, Page 182) and this study documents current state-of-the-art information on placement and compaction of frozen fill materials and other aspects of cold region earthworks. Some of the more relevant information from this study regarding compaction and performance of frozen fills, as it applies to arctic marine structures, is summarized as follows:

- The most suitable type of frozen fill consists of sands and gravels with a low ice content. Although these materials, in a frozen condition, cannot be compacted to densities normally specified in temperate zones, they are generally stable on thawing.
- Frozen clay and silt soils are not commonly used as fills. These soils on thawing are unstable and large deformations should be expected.
- Frozen fills are used only to a limited extent because of potential problems upon thawing of the fill, except where permafrost is expected to rise into the fill.
- Considerable information is available regarding compaction characteristics and limitations to use of various frozen soils.
- Frozen fills can be readily used in applications where only the weight of the soil is required, such as surcharging and stabilizing berms.

4.5 Soil Improvement

4.5.1 General

When confronted with poor soil conditions, it is sometimes practical or even unavoidable to consider soil improvement methods. A wide variety of techniques have been used to improve soil conditions in temperate areas. Very few of these techniques have been used in the arctic offshore areas. The purpose of this section is to briefly review soil improvement techniques which show promise for northern applications.

4.5.2 Methods

Soil improvement methods can be generally divided into two groups:

1) Active soil improvement methods consist of modifying the ground conditions by actively interfering with it. This category includes compaction of seabed by vibro-replacement, and displacement of softer soils by gravity or by blasting. The parameters governing the application of these methods are the same as in temperate areas.

2) Passive soil improvement methods consist of reinforcing or protecting existing soil conditions. For example, soft seabed conditions could be reinforced using filter fabrics (or mats). Thaw unstable seabed conditions could be protected from thaw by artificial refrigeration (use of thermosyphons) or by insulation (with gravel pad, styrofoam or other materials). The parameters governing the application and effectiveness of passive soil improvement methods are site specific and should be carefully evaluated prior to use.

   Thermosyphons have limitations and should be used with caution in offshore applications.

Some of more common methods used in soil improvement are indicated below:

Surcharging

Surcharging is a method normally used in coastal areas to induce settlement due to consolidation of compressible soil strata before a structure is built. This method is not applicable to structures in deep water but could be employed for structures in shallow water where soft sediments are involved.

Vibroflotation Compaction

This method is used to densify loose granular soils by lowering a vibrating tool into the deposit and backfilling with sand. The method has merit in improving loose cohesionless sea bed soils.

Vibro-Replacement (Stone Column)

This method is similar to vibroflotation except that a stone column is left behind after the vibratory probe extraction. It is superior to vibroflotation but is a more complicated procedure.

Blasting

This approach has been used in submerged cohesionless soils to densify the particles. It is applicable only on a level sea bed where there is little chance of downslope movement under the effects of the blasting. There are not sufficient case histories available to show the success of this method.

Grouting

Three types of grouts used in soil stabilization are portland cement, clay and chemical. Grouting trials are desirable for large and/or non routine projects to confirm adequate grout penetration and resulting improvement before full scale grouting is started.

Fabric Reinforcement

Recent developments in the use of fabrics to support embankments on poor soils and to reinforce earth embankments will also find uses in arctic marine construction. The advantages of fabrics are the low cost, easy installation and versitility (2nd Int. Conf. on Geotextiles, Las Vegas, U.S.A. 1982. The papers presented at this conference are published by Industrial Fabrics Association International, 350 Endicott Building, St. Paul, Minnesota 55101).

Artificial Refrigeration

Freezing of unfrozen sea bed soils in the arctic has some merit for consideration because of low sea bed and air temperatures. The types of refrigeration which can be considered are mechanical, thermosyphons or ventilation (natural or forced), although thermosyphons should be used with caution. Thermosyphons may be considered as a type of thermal pile which uses natural convectional systems to remove heat from the ground. It has no moving parts, requires no external power for operation and functions only when air temperatures are lower than the ground temperatures. Various aspects of thermosyphons and thermal pits are reviewed by Johnston (1981).

4.6 Performance Monitoring

4.6.1 General

As discussed in Section 4.2, instrumentation is installed at the time of the site investigation to monitor existing ground conditions. If strategically placed such instrumentation will be most useful in formulating design assumptions which have to be verified during the construction phase either by visual inspection or by instrumentation. After completion of the project visual inspections and site visits can be done regularly to monitor the performance and integrity of the works. However, because of the nature of permafrost, serious and often irreversible deterioration of ground conditions may have already taken place when movement or damage becomes visible. For example, ground temperatures, may have increased and induced thaw settlement or creep of frozen ground resulting in deformation of the structure due to imposition of additional load on it or by yielding support.

Ground instrumentation will allow detection of unusual or unexpected behaviour much before it becomes apparent and in the great majority of cases, significant damage can be prevented.

A well defined data collection program should exist for all instrumentation. Data analyses should be done on a regular basis and be summarized in periodical reports including comments and recommendations if necessary.

The type and number of instruments to be installed on a structure depends on site conditions, the type of structure and its expected behaviour. For northern applications, all instrumentation should be as simple as possible and rugged. A certain redundancy is inevitable to ensure continuing data in the event of instrument failure or malfunction. It should be noted that truly stable datum points (reference bench marks) are absolutely essential for monitoring performance; in particular vertical and lateral movements.

Several aspects of structure behaviour may be monitored. They include:

- temperature
- pore pressure
- vertical deformation
- horizontal deformation
- earth loads

Each of the above is discussed in the following paragraphs with the various devices and methods commonly used for measurement.

4.6.2 Temperature

When the integrity of a structure depends on the stability of the ground thermal regime, it is of utmost importance to monitor ground temperature beneath and around the foundations. Field temperature measurement techniques have been discussed in Section 4.2.3.5.

4.6.3 Pore Water Pressure

It may be necessary to monitor the pore water pressure in unfrozen fine grained foundation soils if they are loaded by an embankment or caisson during construction. Slow pore water dissipation prevents the strength development in the foundation soil and could lead to slope or bearing capacity failure. This can be prevented by controlling the loading rate.

Pore water pressure can be measured by standpipe, pneumatic or electrical piezometers. The first two must be read manually while the latter can be recorded automatically.

4.6.4 Vertical Deformation

Vertical deformation is normally observed to confirm the estimated settlement which can affect the operation of the structure or connections to external structures. Vertical deformation may be due to unfrozen soil compression or consolidation, thaw consolidation or frost heave.

Normally vertical deformation is monitored by level survey of established points. Other methods such as buried plates with rods protruding through casings (settlement plates) or electrical extensometers can be used.

4.6.5 Horizontal Deformation

When the integrity of a structure depends on its base sliding resistance or when it is subjected to very high lateral loads, monitoring of horizontal deformation is important. Situations involving earth cells, caissons resisting lateral loads totally or partly by base shear resistance or a steeply sloping seabed, all require carefull monitoring of horizontal deformation.

Monitoring horizontal deformation is accomplished with inclinometers which have to be installed in a borehole and solidly grouted in place or with alignment pins. Precise surveying of permanent markers stragegically located on the structure is the simplest and most cost effective way of monitoring horizontal deformations.

4.6.6 Earth Loads

Monitoring of earth loads is not routinely carried out in geotechnical engineering but there may be some special situations where it is required. Earth cells are used for this purpose. They consist of either pneumatic or strain gauge devices reacting proportionally to the applied load.

CHAPTER 5

RESPONSES TO THE ICE ENVIRONMENT

5. RESPONSES TO THE ICE ENVIRONMENT

5.1 Ice Attack on Structures

Figure 5.1 illustrates various modes in which ice may attack an offshore or a coastal structure. Planning and conceptual design will aid in reducing thrust effects. Features must be provided to resist effects which cannot be eliminated. Average properties of cold service are given on Table 5.1.

5.1.1 Effects on Development

Ice effects vary depending on the type of development.

Ice is an obstacle to marine structures in the form of:

- Global ice forces;
- Local ice forces;
- Ice ride up.

Ice is an obstacle to coastal structures, ports and navigation aids through:

- Ice thrust;
- Ice weight and uplift;
- Ice ride up;
- Ice rubble generation;
- Shore ice mounds.

Ice is an obstacle to floating structures as a result of:

- Ice thrust;
- Superstructure icing;
- Isolation.

Ice is an obstacle to navigation as a result of:

- Pack ice forces;
- Ice pressure in shipping lanes and mooring areas;
- Risk of icebergs;
- Superstructure icing.

Ice is an obstacle to buried structures, pipelines, cables from:

- Ice scour.

For operations, natural conditions are important. Extreme events lead to catastrophic failures.

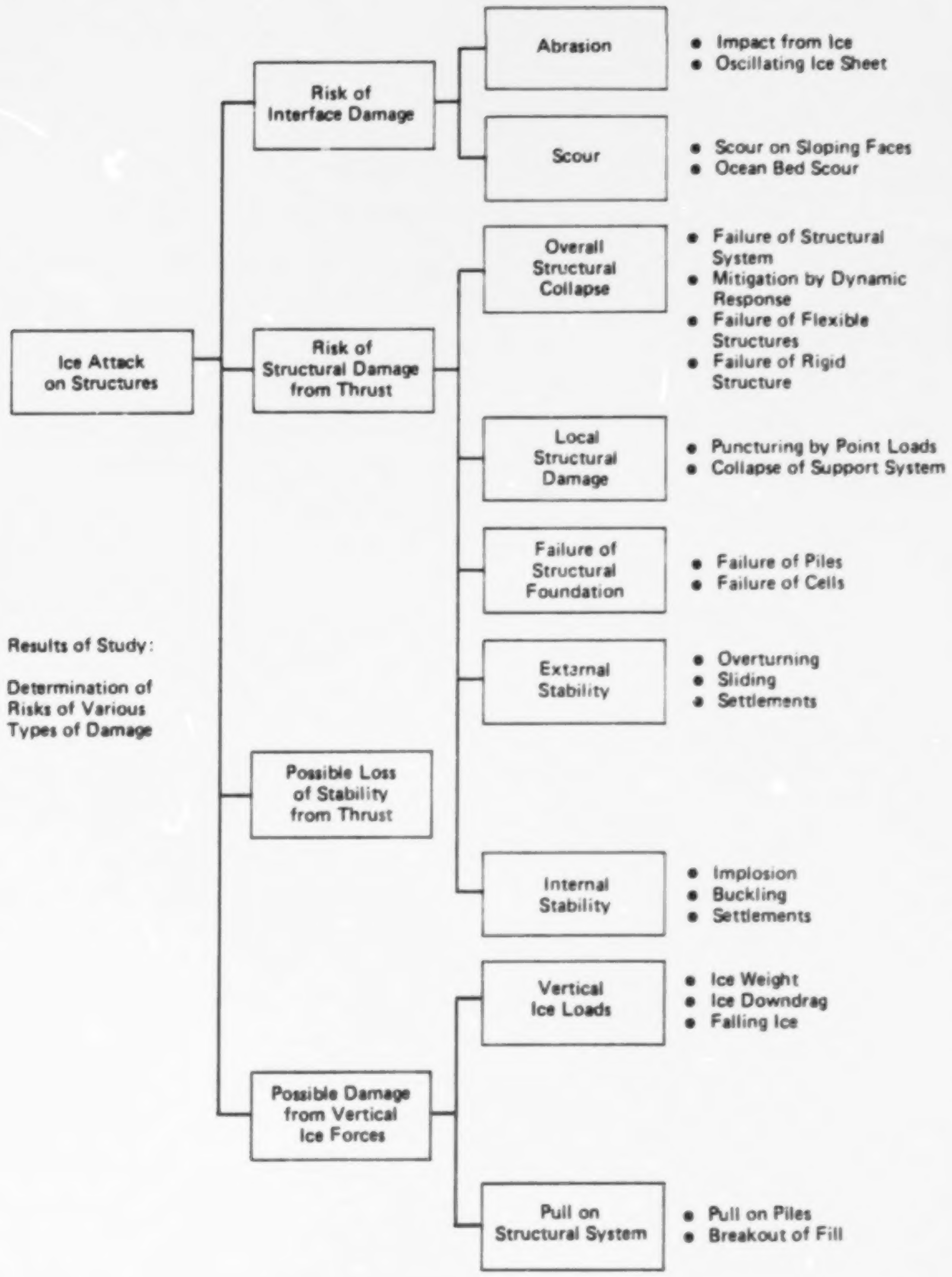

Ice Attack on Structures
Risk of Interface Damage
Abrasion
• Impact from Ice
• Oscillating Ice Sheet
Scour
• Scour on Sloping Faces
• Ocean Bed Scour
Risk of Structural Damage from Thrust
Overall Structural Collapse
• Failure of Structural System
• Mitigation by Dynamic Response
• Failure of Flexible Structures
• Failure of Rigid Structure
Local Structural Damage
• Puncturing by Point Loads
• Collapse of Support System
Failure of Structural Foundation
• Failure of Piles
• Failure of Cells
External Stability
• Overturning
• Sliding
• Settlements
Possible Loss of Stability from Thrust
Internal Stability
• Implosion
• Buckling
• Settlements
Possible Damage from Vertical Ice Forces
Vertical Ice Loads
• Ice Weight
• Ice Downdrag
• Falling Ice
Pull on Structural System
• Pull on Piles
• Breakout of Fill
Results of Study:
Determination of Risks of Various Types of Damage

Figure 5.1 Various Modes of Ice Attack on Offshore or Coastal Structure

	Pressure in kPa
A. Ice Strength and Energy	
1. Maximum unconfined compression	8,000
2. Maximum local pressure in confined compression	24,000
3. Maximum tensile strength	2,600
4. Maximum shear strength	1,300
B. Modulus of Elasticity	
1. Solid ice	3,200,000
2. Virtual modulus of broken pack	200,000
C. Pressure from Energy to Failure	
1. Breakdown of ice edge (low velocity)	
i. Flaking energy	500
ii. Breaking energy in confined loading	1,000
iii. Average energy in steady crumbling of ice edge	750
2. Pressure at the moment of impact	
i. Dynamic limit pressure in solid ice sheet	1,870v*
ii. Dynamic limit pressure in uniform pack	470v*
3. Pressures during penetration of ice	
i. Average energy during incision into compact pack ice	900v*
ii. Maximum pressure during identation which dislodges part of compact ice	1,550v*

*v - The speed of impact in m/s

References (Boss 1977) (Kivisilis 1977, Iyre 1980)

Table 5.1 Average Properties of Cold Sea Ice

Global Ice Loading

Massive solid ice formations such as icebergs, ice islands, multi-year ice floes, and annealed ridges cause extreme loads on impact. They could be driven by winds, currents or pack ice.

The global force is an oscillating phenomenon. In bending failures, large variations occur.

Fracture Mechanism

Crushing	High stresses can exist locally but the energy required to crush the ice corresponds to an average stress in the order of at most 2 MPa, lowered to about 1 MPa for very wide structures.
Shearing	The short-term shear resistance varies from 300 to 3000 kPa.
Flexure	The general flexural strength of the ice sheet not only depends on the ice strength but is also affected by crack patterns. The flexural strength varies from 300 to 2000 kPa.

Local Ice Loading

It is recognized that certain locations on the structure will experience higher than average pressure and may thus require local stiffening designed to withstand local high pressures.

The local pressure is related to the confined crushing strength of the ice and can be one order of magnitude higher than the simple compressive strength.

The local pressures are oscillating loadings, varying much more rapidly than the global pressure. The local pressure variations are mainly due to the crushing mechanism itself.

Sea ice may be estimated to exert pressures from 10,000 to 20,000 kPa on structure panels. Iceberg pressures could reach 30,000 kPa.

Ice Pile-Up and Rubble Generation

Rubble grounding on a part of the structure and generating a pile-up will reduce direct thrust on a structure. The heights of pile-ups depend on the geometry of the structure and depth of water.

Range of Scour

The seabed in the Arctic Seas is covered by scours which are caused by deep keels of various ice features.

The number and depth of scours are very site specific. In general, in the Arctic Seas they vary from 0 in depths greater than 100 m to 100 per km in water depths of 30 m.

In the Labrador waters, icebergs have caused scour water depths up to 100 m.

Scour depths vary from a few centimetres to several metres and the width can extend to 100 m. Deepest known scour is 10 m in the Herschel Canyon.

Ice Ride Up

There is the possibility of ice ride up onto work areas. Ride up of 10 m has been observed.

Structural Icing

Ice accretion on vessels and drill rigs may reach hazardous levels in the arctic. Ice accretion over 10 cm could be formed by freezing precipitation and by freezing spray.

Vertical Loads

Ice weight and uplift effects have caused damages to arctic structures.

5.2 Alternative Solutions

Major alternatives solutions are identified below:

a) Ice Control - heavy sea ice effects can be mitigated or completely eliminated by such means as Ice Diversion, Ice Suppression, Ice Breaking or Ice Removal.

b) Avoiding Ice - weather windows can be selected for operation, resources and materials can be transported by air or submarines, and drilling can be performed during open water or mild ice seasons.

c) Utilizing Ice - overice transportation includes construction of airstrips and ice roads. Drilling platforms can be constructed by building up ice and protective barriers can be built of rubble to reduce ice forces on artificial islands.

d) Resistance to Ice - ice resistant structures or vessels can be used or protective elements can be added.

Options available to provide arctic marine structures and their operational consequences are presented in Figure 5.2.

5.2.1 Ice Management

The management of first-year ice does not present a major problem. The main concern exists with the management of icebergs and multi-year ice.

Sea ice management alternatives for overcoming ice obstacles can be divided into several methods. Each method has undergone extensive research but requires much further development. A list of existing and proposed ice management techniques is presented in Table 5.2.

5.2.2 Ice Resistant Structures

Refers to the ability of a fixed structure or vessel to withstand ice impact forces.

The design of arctic marine structures has included the development of a variety of platform concepts for year round drilling. Structures, caissons and artificial islands.

Initially, fixed above-sea earthfill structures such as sacrificial beach islands, were constructed in the shallower waters in the Beaufort. By the Spring of 1982, 20 such artificial islands had been built demonstrating the capability to withstand winter ice. Recently, mobile bottom founded gravity and floating platforms have been developed. These have included earthfill caisson retained structures (such as Tarsuit, Esso Caisson Systems and Mobile Arctic Caisson of Gulf) caisson gravity structures (such as the modified tanker SSDC), and conical structures, full height or on a mound have been proposed (Figure 5.3).

Essentially, unconfined islands can resist all ice action but becomes rapidly more expensive with increasing water depth, having economic limitations at about 20 m even with special scour protection.

Confined islands are practical to greater water depths and may be extended to 30 m.

Gravity structures which can resist icebergs have been conceptually designed for waters up to 200 m but none has been implemented. Iceberg resistance gravity platforms on earthfill mound have been shown to be feasible.

Ice resistant wharves have been created in the eastern and western arctic waters. They range from pile structures successful in Cook Inlet to heavy cells at Deception Bay, Nanisivik and Little Cornwallis.

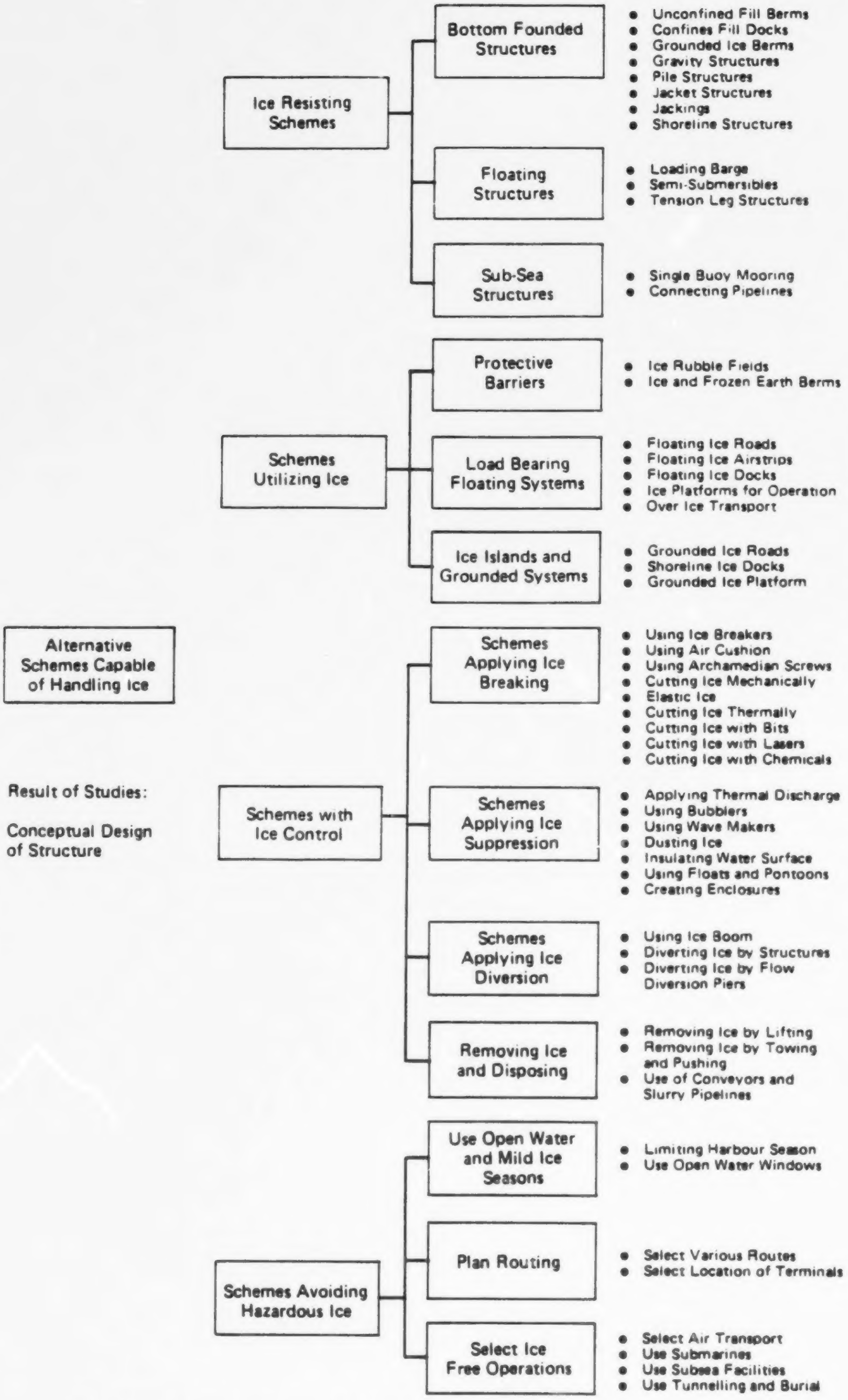

Alternative Schemes Capable of Handling Ice
Result of Studies:
Conceptual Design of Structure
Ice Resisting Schemes
Bottom Founded Structures
Unconfined Fill Berms
Confines Fill Docks
Grounded Ice Berms
Gravity Structures
Pile Structures
Jacket Structures
Jackings
Shoreline Structures
Floating Structures
Loading Barge
Semi-Submersibles
Tension Leg Structures
Sub-Sea Structures
Single Buoy Mooring
Connecting Pipelines
Schemes Utilizing Ice
Protective Barriers
Ice Rubble Fields
Ice and Frozen Earth Berms
Load Bearing Floating Systems
Floating Ice Roads
Floating Ice Airstrips
Floating Ice Docks
Ice Platforms for Operation
Over Ice Transport
Ice Islands and Grounded Systems
Grounded Ice Roads
Shoreline Ice Docks
Grounded Ice Platform
Schemes with Ice Control
Schemes Applying Ice Breaking
Using Ice Breakers
Using Air Cushion
Using Archamedian Screws
Cutting Ice Mechanically
Elastic Ice
Cutting Ice Thermally
Cutting Ice with Bits
Cutting Ice with Lasers
Cutting Ice with Chemicals
Schemes Applying Ice Suppression
Applying Thermal Discharge
Using Bubblers
Using Wave Makers
Dusting Ice
Insulating Water Surface
Using Floats and Pontoons
Creating Enclosures
Schemes Applying Ice Diversion
Using Ice Boom
Diverting Ice by Structures
Diverting Ice by Flow Diversion Piers
Removing Ice and Disposing
Removing Ice by Lifting
Removing Ice by Towing and Pushing
Use of Conveyors and Slurry Pipelines
Schemes Avoiding Hazardous Ice
Use Open Water and Mild Ice Seasons
Limiting Harbour Season
Use Open Water Windows
Plan Routing
Select Various Routes
Select Location of Terminals
Select Ice Free Operations
Select Air Transport
Use Submarines
Use Subsea Facilities
Use Tunnelling and Burial

Figure 5.2 Alternative Schemes Capable of Handling Ice and their Operational Consequences

]

Regional Ice Management Techniques	Method	Beaufort Sea	Arctic Islands	Hudson Bay	Baffin Bay	Labrador	Hibernia
Ice Control							
Ice Breaking	Ice Breakers	E	P	E	P	E	
Ice Suppression	Bubblers in Ports	P		P		P	
	Atoll Offshore Port	P					
Ice Diversion	Iceberg Towing					E	E
Ice Removal	Clearing of Ports						
Ice Resistance							
Structures	Unconfined Earth Islands	E					
	Confined Earth Islands	E					
	Grounded Ice Islands	P					
	Gravity Platforms	E				P	P
	Jacket Structures						P
	Jack-ups						
	Tension-Leg Platforms						P
	Harbour Caissons	E	P	E		E	
Vessels	Ice Strentghened Vessels	E		E	P	E	E
	Semi-Submersibles	P				P	E
	Production and Drilling						
	Barge	E					
Ice Evasion	Tunnelling	P	P			P	
	Burial of Pipelines	P	P			P	P
	Submarine Tankers		P		P		
	Precast Systems		P		P		
	Operating During Fair						
	Weather Windows	E	E	E	E	E	E
	Air Transportation	E	E	E	E	E	E
	Surface Effect Vehicles		P				
Ice Use	Drilling Platforms	P	E				
	Transportation Routes	E	E				
	and Facilities						
	Protective Barriers	E	P				

E – Existing
P – Proposed

Table 5.2 Existing and Proposed Ice Management Techniques in the Canadian Arctic

Jacket type structures have been used in the moderately heavy ice conditions of Cook Inlet but have not been shown to be feasible in these heavier arctic ice areas.

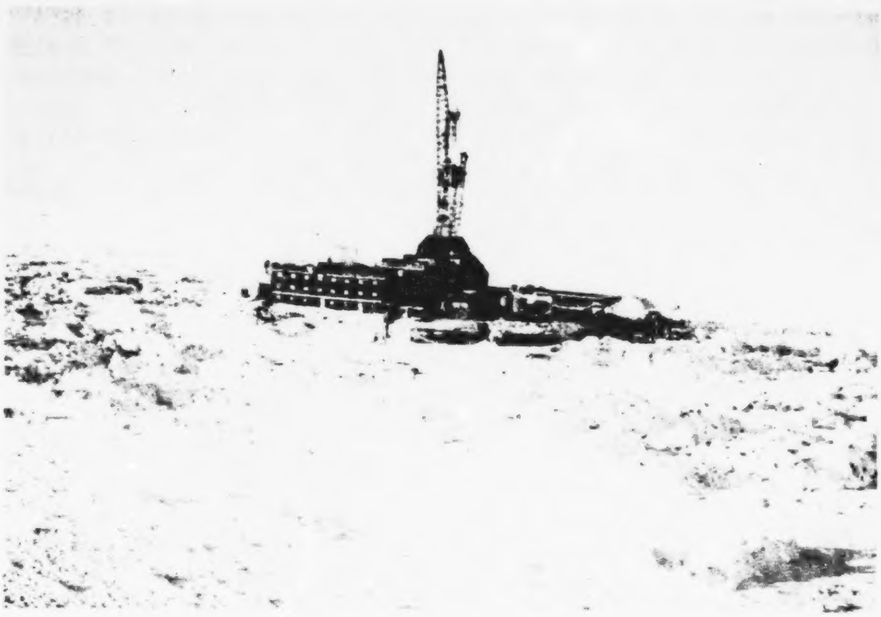


Figure 5.3 Caisson-Retained Ice Resistant Island Forming Rubble Field and Reducing Direct Ice-Island Impact Forces.

5.2.3 Vessels

Includes drill ships, specifically designed ice breakers, ice breaking ships and ice-strengthened ships. A special case is the conical anchored drilling vessel designed for larger ice loads.

Ice-strengthened ships have additional steel added to sections of the hull to improve ice-breaking capability and safety. An example of this is the Class 2 cargo vessel M.V. Arctic. Such vessels can operate throughout the year in some arctic waters but must have icebreaker support during the winter.

Ice Breaking Ships - such as tankers and cargo vessels are specifically designed to operate year-round in ice affected waters without icebreaker assistance. In Canada a vessel requires minimum Class 8 specification in order to operate in the Northwest Passage. Such large size commercial vessels have yet to operate in the Arctic.

Semi-submersible and jack drilling platforms operating in the deeper waters off the East Coast are moderately strengthened but are not designed for full ice resistance. They are mobile and supported by iceberg tow vessels and follow a management practice of ice avoidance.

5.2.4 Utilizing Ice

Ice as an obstacle can be overcome by employing it is as a construction material. This is done extensively in the Beaufort and Arctic Island regions with the development of economical overice transportation routes and facilities in the form of roads and airstrips (Figure 5.4). Structures have been erected from ice. Pipelines have been placed from ice.

Figure 5.4 Extensive Use of Ice Roads in the Beaufort Sea Arctic Islands for Transporting Equipment and Constructing Artificial Islands.

The most recognized use of ice has been as a support structure for offshore drilling operations. Panarctic Oils Ltd. has effectively used ice platforms for this purpose in the past 10 years and 46 platforms have been built. The use of ice has made it possible to drill offshore in the Sverdrup Basin as economically as drilling onshore there.

Recently, ice has also been recognized as a protective barrier. Ice has been used in the construction of a berm to protect an underwater gas pipeline in shallow waters from the effects of scour. The extensive rubble fields which have developed around vertical walled caissons have protected artifical islands from the direct effects of ice impacts.

5.2.5 Ice Control

A detailed report on the subject of ice management has been prepared for the Department of Transport by Acres - Vol. 2, Appendix 2). A summary of the content is outlined as follows:

Refers to the various methods by which heavy sea ice conditions can be controlled. They include such techniques as:

> Ice Breaking - which is the bending, breaking, crushing and shearing of ice and includes such techniques as conventional icebreakers, air cushion vehicles, explosive, and mechanical, thermal and chemical ice cutters that allow the passage of a vessel. Offshore ice breaking is essentially accomplished by icebreakers in Arctic waters. Ice cutting has been considered in open waters, whereas other techniques would primarily be used in ports and harbours.
>
> Icebreakers are undergoing engineering changes, making work in the arctic more promising. Water jets, air bubblers and cutting devices have been tried adding new features to the method of breaking only with the hull.
>
> Ice Suppression - which is the prevention of ice formation and includes such techniques as thermal discharge, bubblers, enclosures and insulation.
>
> Bubblers have been very successful in the St. Lawrence River and Great Lakes area. Different conditions in sea waters indicate equal success in sea waters is not likely. Flow generators have been shown to have beneficial effects.
>
> Thermal discharge from ships and plants, enhanced by enclosures and insulation has been shown to suppress ice significantly.
>
> Ice Diversion - which is the deflection of moving ice floes and icebergs to prevent collisions with harbour structures and drilling platforms including such techniques as iceberg towing, booms, artificial structures, flow developers and wave-making devices.
>
> The most common iceberg control techniques proposed are destroying and towing. Destroying the bergs with explosives has met with little success. Surface charges do little but scar and flake the outer surface of the berg, most of the energy being dissipated into the air. Explosives placed at some depth into the berg may be able to utilize the iceberg's internal stress to help destroy it. Towing icebergs has been shown to be a feasible solution for iceberg management and has met with considerable success (Figure 5.5).

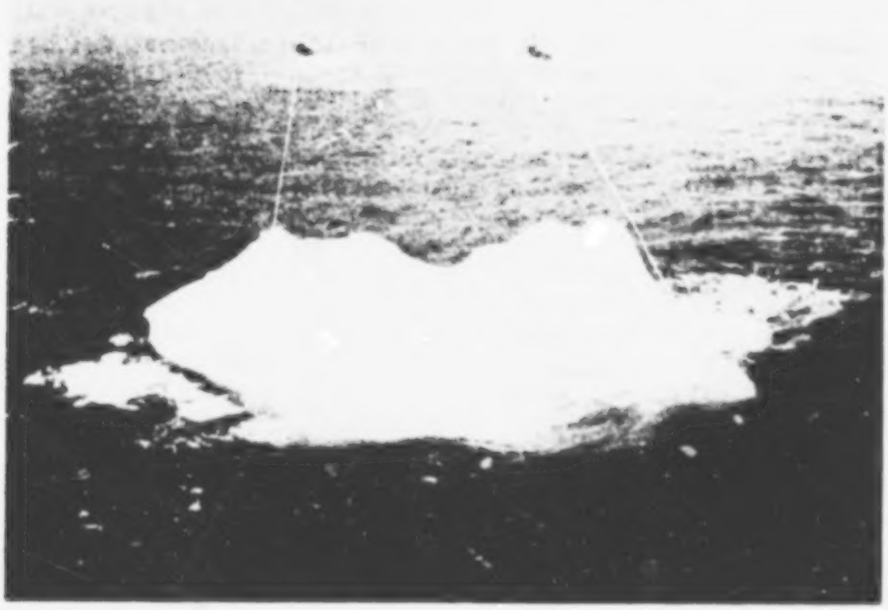


Figure 5.5 Vessels towing away an Iceberg

Iceberg impact absorption/deflection techniques have been suggested using various moored arrays or fixed bottom structures on rubble piles. None have been taken beyond the concept stage. Further work could be profitably done in this area.

Heavy fenders have been proposed to decelerate and to deflect icebergs from dangerous paths.

Icebreakers which operate primarily in a support capacity and are used to open shipping channels for supply vessels as well as breaking and re-directing ice ridges and pack ice floes drifting towards drill ships and bottom-anchored platforms.

Ice Removal - which involves the physical displacement of ice by such methods as lifting, submerging, pushing, or piping and which require excavation and piping equipment.

Ice cutting by mechanical means combined with removal by modified construction and transport equipment were included in Polarquest study in 1970 and in a system of air cushion drilling platforms in a slowly moving ice cover. The technical feasibility of these systems was definitely proven.

Rotary ice cutters attached to structures and vessels have been shown to be able to penetrate most sea ice formations by cutting and disposal of ice floes and ridges.

5.2.6 Avoiding Ice

Refers to the completion of operations during ice-free or minimum ice concentration periods, and to the placement of structures out of harms way.

Various ice evasion methods include:

- exploring for oil and gas during the open water season. this is generally completed in the Beaufort by drill ships;
- selecting fair weather windows during the summer period for the transportation of natural and man-made materials;
- transporting equipment and materials by cargo planes throughout the winter period;
- proposals for transporting crude oil and liquid natural gas by submarine tankers, particularly in the Arctic Islands, however, none of these proposals have been advanced beyond the design and feasibility stages;
- air cushion drilling system has been shown to be mechanically feasible in the Arctic Archipelago;
- placing wellheads in glory holes or caissons below the keel of ice action;
- burying pipelines below scour depth or protecting pipelines with ice and gravel berms (Figure 5.6);
- tunnelling access to wellheads from shore, which has been proposed for arctic islands and nearshore Labrador developments.

These methods have formed an important repertory in developing Beaufort Sea basins.

Figure 5.6 Protective Barrier of Ice and Gravel Built Around a Natural Gas Pipeline to Prevent the Effects of Ice Scour.

CHAPTER 6

EXISTING REGULATIONS AND STANDARDS

6. EXISTING REGULATIONS AND STANDARDS

At the present time, existing regulations and standards are incomplete. This chapter of the Handbook presents a summary of information currently available and it also provides a detailed information on the multitude of approvals and regulations that must be taken into consideration before undertaking any engineering and or exploration work in the Canadian North.

6.1 Ice Aspects in Design

6.1.1 Canadian Standards Association

Offshore ice force design codes are being prepared. At present existing guidelines are presented in Code S6 (1978) Design of Highway Bridges (Volume 2, Appendix 1) - While this Canadian code is specifically intended for inland bridge structures, it is often used as a basis for offshore design criteria. The section of the code dealing with ice forces is reproduced below:

> General
>
> Ice forces on piers shall be selected having regard to site conditions and the mode of ice action to be expected. Consideration shall be given to the following modes:
>
> a) Dynamic ice pressure due to moving ice-sheets and ice-floes carried by streamflow, wind, or currents;
>
> b) Static ice pressure due to thermal movements of continuous stationary ice-sheets on large bodies of water;
>
> c) Static pressure resulting from ice-jams;
>
> d) Static uplift or vertical loads resulting from adhering ice in waters of fluctuating level.
>
> The expected thickness of ice, the direction of its movement, and the height at which it acts shall be determined by field investigations, published records, aerial photography and other means. Consideration shall be given to the worst expected combination of height, thickness, and pressure, to the possibility of unusual thicknesses resulting from special circumstances or operations, and to the natural variability of ice conditions from year to year.

Dynamic Ice Force

Horizontal forces resulting from the pressure of moving ice are to be calculated by the formula:

$$F = C_n ptw \qquad (6.1)$$

where: F = horizontal ice force on pier, kN

C_n = coefficient for nose inclination from table

p = effective ice strength, kPa

t = thickness of ice in contact with pier, m

w = width of pier or diameter of circular-shaft pier at the level of ice action, m

Inclination of Nose To Vertical, Degrees	C_n
0 - 15	1.00
15 - 30	0.75
30 - 45	0.50*

* Alternatively, the coefficient for a nose inclination greater than 30° may be calculated on the basis of effective bending strength of ice.

The effective ice strength shall normally be taken in the range of 700-2800 KPa on the assumption that crushing or splitting of the ice takes place on contact with the pier. The value used shall be based on an assessment of the probable condition of the ice at time of movement, on previous local experience, and on assessment of existing structure performance.

Note: Relevant ice conditions include the expected temperature of the ice at time of movement, the size of moving sheets and floes and the velocity at contact. Due consideration should be given to probability of extreme rather than average conditions at the site in question.

The following values of effective ice strength appropriate to various situations may be used as a guide:

a) In the order of 700 kPa where break-up occurs at melting temperatures and where the ice runs as small "cakes" and is substantially disintigrated in its structure;

b) In the order of 1400 kPa where break-up occurs at melting temperatures, but the ice moves in large pieces and is internally sound;

c) In the order of 2100 kPa where at break-up there is an initial movement of the ice sheet as a whole or where large sheets of sound ice may strike the piers; and

d) In the order of 2800 kPa where break-up or major ice movement may occur with ice temperature significantly below the melting point. The preceding values for effective ice strength shall be used with piers of substantial mass and dimensions. The values shall be modified as necessary for variations in pier width or pile diameter, and design ice thickness by multiplying by the appropriate coefficient obtained from Table 6.1.

b/h	Coefficient
0.5	1.8
1.0	1.3
1.5	1.1
2.0	1.0
3.0	0.9
4.0 or greater	0.8

Table 6.1 Pier Coefficients

where: b = width of pier or diameter of pile

h = design ice thickness

Static Ice Pressure

Ice pressure on piers frozen into ice sheets on large bodies of water shall receive special consideration where there is reason to believe that the ice sheets are subject to significant thermal movements relative to the piers.

Code S6 (1978) Design of Highway Bridges (Volume 2, Appendix 1) is a development of a previous code (Old CSA Highway Bridge Code) which is often referred to in the literature. The old code did not take into account the angle of a sloping column or pier and used a constant value for crushing strength of 400 psi (2760 kPa).

6.1.2 American Association of State Highway and Transportation Officials: Standard Specifications for Highway Bridges (1973 - Volume 2, Appendix 1)

This code accounts for impact ice load very briefly as follows:

All piers and other portions of structures which are subject to the force of flowing water, floating ice, or drift shall be designed to resist the maximum stresses induced thereby. The pressure of ice on piers shall be calculated at 400 pounds per square inch. The thickness of ice and height at which it applies shall be determined by investigation at the site of the structure.

6.1.3 USSR Standard SN76-66

The USSR code is designed for bridges in the USSR. Relevant sections of this code, as it pertains to the design of piers with vertical leading edges and with sloping leading edges, subject to ice forces, may be used in the design of arctic marine structures.

6.1.4 Det Norske Veritas: Rules for the Design, Construction and Inspection of Offshore Structures (1977 - Volume 2, Appendix 1)

This Norwegian code gives general instructions for the design of structures to be located in an area where ice may develop or drift.

Relevant statistical data on the ice conditions are to be submitted if ice hazard may exist. Sea ice conditions are to be described with particular attention to:

- concentration and distribution of ice,
- type of ice (ice floes, ice ridges, rafted ice, etc.)
- mechanical properties of ice
- drifting speed and direction
- thickness of ice
- probability of encountering icebergs

The assumed conditions as regards icing on the structure are to be described with particular attention to concentration, distribution and thickness of ice.

The description of ice conditions should preferably be in accordance with the "World Meteorological Organization Sea Ice Nomenclature."

Loads from laterally moving ice are to be based on relevant full scale measurements, model experiments which can be reliably scaled or on recognized theoretical methods. When determining the magnitude and direction of ice loads, considerations are to be given to the nature of ice, mechanical properties of the ice, ice structure contact area, shape of structure, direction of ice movements and the oscillating nature of the ice loads (build up and fracture of moving ice).

6.1.5 American Petroleum Institute: Recommended Practice RP 2A (1982) Planning, Designing and Constructing Fixed Offshore Platforms (Volume 2, Appendix 1)

This recent edition of the API code is the most comprehensive set of guidelines prepared to date which specifically refer to offshore platforms in ice-affected waters, however, it only describes ice forces or structures in relation to the regional ice characteristics of the Alaskan Beaufort. As such, ice feature characteristics (such as icebergs) and environmental conditions associated with the east coast and Arctic Islands are not addressed. The document does, however, provide an excellent basis for establishing recommended practices for these and other ice-affected regions.

Details of ice loading are in Bulletin 2N: Planning, Designing and Constructing Fixed Offshore Structures in Ice Environments.

6.1.6 Other Codes and Standards

Other European Codes of interest are:

1. Polish Standard PN-66/B-02015 (1970) - This code is for the design of inland bridges and takes ice pressures into consideration.

2. Finish Design Code: Specifications of loads of Structures (1969) - This code is unique in that it relates to the bridge opening piers rather than to pier width.

6.2 Geotechnical Aspects in Design Codes and Guidelines

"Geophysical and Geological Programs on Canada Lands - Guidelines for Approvals and Reports" dated March 1984 published by Canada Oil and Gas Land Administration (COGLA), Tower "B", Place Vanier, 355 River Road, Vanier, Ontario, defines the procedures required to undertake any geophysical/geological work on Canada lands. This publication also lists various Federal agencies having jurisdiction and should be consulted and satisfied before, during and on completion of work, inshore and offshore, in Canada.

At this time there are no codes in Canada dealing specifically with the design and construction of structures and facilities on permafrost or in the arctic offshore. The general foundation requirements of Part 4 of the National Building Code of Canada are often used as reference for structures covered by the code. The Canadian Foundation Manual (Canadian Geotechnical Society 1978 - Volume 2, Appendix 1) includes pertinent information to guide foundation design.

Information pertinent to geology and seismicity can be obtained from:

- Geological Survey of Canada (memoirs, papers and miscellaneous publications - Volume 2, Appendix 1)

- Pacific Geoscience Center (seismic risk analysis for specific sites - Volume 2, Appendix 1).

A number of Soviet codes, books or instructions for design and construction of structures in the North have been translated into English, but none address offshore construction.

Among several books published in the last few years, the following are good sources of information:

- Permafrost, Engineering Design and Construction (Johnston 1981 - Volume 2, Page 196)

- Geotechnical Engineering in Cold Regions (Andersland and Anderson 1978 - Volume 2, Page 171).

6.3 Structural Codes and Standards

6.3.1 Structural Steel

In North American practice, steel structures in the arctic are usually designed in accordance with the provisions of API Bulletin 2N ("Bulletin on Planning, Designing and Construction of Fixed Offshore Structures in Ice Environments", American Petroleum Institute, Dallas, Texas, 1981) and the structural steel design code of AISC (USA) or CSA-S16 (Canada - Volume 2, Appendix 1). These codes are generally based on the working stress method of design.

In European practice, arctic steel structures are usually designed to DnV rules ("Rules for the Design, Construction and Inspection of Offshore Structures", Det noske Veritas, Oslo, Norway 1977 - Volume 2, Appendix 1). These rules use the limit state design approach. Other design rules used are the ABS ("Rules for Building and Classing Steel Vessels", American Bureau of Shipping, New York 1981 - Volume 2, Appendix 1), the CASPPR regulations ("Canadian Arctic Shipping Pollution Prevention Regulations", Canadian Ministry of Transport, Ottawa 1979 - Volume 2, Appendix 1) and the Finnish Rules. These rules and regulations strictly apply to the design and checking of hull-strength for ships, but may be lifted from this context to apply to any steel- skin structure stiffened by frames or ribs.

Corburn (1981- Volume 2, Appendix 1) has reviewed hull ice-strengthening criteria from the above rules. He pointed out that traditional ship rules are rather empirical and suggest substantially more optimistic criteria than the CASPPR regulations.

Coburn proposed a rational procedure which selected the ice feature and properties and developed scantling and plate sizes based on the predicted pressures. Section properties in fact were developed by means of plastic analysis of both plates and supporting frames. As in the case of the COSSAC structure mentioned above, Coburn recommends the use of plastic design procedures for the hull plate. He quotes U.S. Coast Guard experience, that failures which have taken place have been almost totally confined to the supporting frames and not to the plates themselves.

There is no single design code which addresses the problems of designing arctic steel structures. The API bulletin addresses some of these problems in a very preliminary fashion. At this time, we are much in need of a rational overall design procedure which starts with definition of the ice feature and ends with selection of member sizes. This is particularly important when dealing with sea-ice which can pose substantially higher local pressures than may be assumed for average pressures in computing forces applied to large sections of the structure. What is of concern here is the potential for progressive collapse associated with high localized loading.

The design and details of welds for connections are generally in accordance with AWS D.1 - 1979 or CSA W59 - 1982 (Volume 2, Appendix 1).

6.3.2 Concrete Structures

In North American practice, reinforced concrete or prestressed concrete structures in arctic marine environment are generally designed to ACI 357 R-78 ("Guide for the Design and Construction of Fixed Offshore Concrete Structures", reported by ACI Committee 357, American Concrete Institute, Detroit, Michigan 1981 - Volume 2, Appendix 1) and the conventional concrete structural code ACI 318, 1983 (USA - Volume 2, Appendix 1) or CAN3-A33.3-M77 (Canada). The limit state design approach is favoured.

These guidelines refer to different ice formations to be expected in ice-affected regions and include first-year, multi-year ice features, consolidated and unconsolidated ice ridges, ice islands and icebergs. The API Bulletin 2N, on the other hand, is referred to for the design guidance in estimating ice loadings.

It is to be noted that ACI 357R-84, edition, will shortly be published.

In European practice, the DnV rules are generally used. These rules are very similar to the North American practice.

Like steel structures in the arctic, there is no single design code or rule applicable for designing concrete structures in the arctic environment.

This is particularly true in the case of the structural problems created by the high local ice pressures. Such local (confined ice pressures) pressures may average 7 MPa (1000 psi) or more over a limited contact area, and results not only in large bending forces but also very large punching shear stresses. These forces impose severe penalties on the concrete structure and have led to AOGA Project 152 ("Punching Shear Resistance of Concrete Shells and Slabs", Alaska Oil and Gas Association 1982 - Volume 2, Appendix 2).

Prestressing assists in reducing concrete shell thickness by increasing both the shear and bending capacity. It is anticipated that most concrete arctic structures will have some prestressed concrete elements, if only for crack control.

6.4 Material Standards

6.4.1 Structural Steel

Steel material in arctic marine structures must be carefully chosen to avoid the occurrence of brittle fracture.

Simply stated, brittle fracture is the inability of the material at a given temperature to react, either elastically or plastically, to an applied tensile stress immediately in front of a crack or crack-like discontinuity. Brittle fracture does not occur under compressive stress regimes and only occurs under the following conditions:

- Very low temperature
- Presence of cracks or flaws
- Presence of tensile stresses
- Dynamic loading

However, the importance of each item is only relative. Certain steels may be subject to brittle fracture even at non-freezing temperatures. A large flaw may be quite harmless in one location, but located in an area of high tensile stress, a small flaw may be catastrophic. While dynamic loading may initiate brittle fracture, a change in static loading could have the same end result. Tensile stress need not originate from applied loading, but may result from residual stresses from rolling or welding.

The approach normally taken to minimize the risk of brittle fracture is to specify the use of materials with a minimum certified notch toughness (absorbed energy in joules or foot-pounds) at a given test temperature (°C or °F) as given by a standard Charpy V-notch impact test on small specimens. There is some question how these test results can be directly related to a steel structure in the field. However, it does give a qualitative measure of assurance against brittle fracture. Recommended Charpy values for various service conditions are given in the DnV Rules.

Other qualities to look for in the steel material are weldability, corrosion resistance, abrasion resistance and good through-thickness properties.

Notch tough steels suitable for low temperature applications are produced in Canada to Specifications CAN3-G40.21-M81 in the following types:

• Type WT	Weldable Notch Tough Steel
• Type AT	Atmospheric Corrosion-Resistant Weldable Notch Tough Steel
• Type QT	Quenched and Tempered Low Alloy Notch Tough Steel Plate

American Steel Specifications suitable for low temperature application are as follows:

• ASTM A537 Class 1 and 2	Used for offshore platforms and refrigerated gas cargo tanks
• ASTM A678 Grade A & B ASTM A710 Grade A	Used in hull structures for ice breakers and low temperature pipelines to -46°C
• ASTM A737	Down to -62°C
• ASTM A533	Down to -170°C
• ASTM A645 Pressure Vessel Quality	Used to -196°C

6.4.2 Reinforced and/or Prestressed Concrete

Concrete has been used successfully in arctic marine structures for some time. Unlike steel, concrete properties such as strength and stiffness actually improve with low temperatures. However, the concrete mix must be designed to resist ice abrasion, freeze-thaw action and local impact from ice-floes in order to achieve a durable structure.

The following recommendations are from ACI 357R-78 "Guide for the Design and Construction of Fixed Offshore Concrete Structures".

Durability

Proper ingredients, mix proportioning, construction procedures, and quality control should produce durable concrete. Hard, dense aggregates combined with a low water-cement ratio and moist curing have produced concrete structures which have remained in satisfactory condition for 40 years or more in a marine environment.

The three zones of exposure to be considered on an offshore structure are:

(a) The submerged zone, which can be assumed to be continuously covered by the sea water.

(b) The splash zone, the area subject to continuous wetting and drying.

(c) The atmospheric zone, the portion of the structure above the splash zone.

Items to be considered in the three zones are:

(a) Submerged zone - Chemical deterioration of the concrete, corrosion of the reinforcement and hardware, and abrasion of the concrete.

(b) Splash zone - Freeze-thaw durability, corrosion of the reinforcement and hardware and the chemical deterioration of the concrete, and abrasion due to ice.

(c) Atmospheric zone - Freeze-thaw durability, corrosion of reinforcement and hardware, and fire hazards.

Cement

Cement should conform to Type I, II, or III portland cements in accordance with ASTM C150 and blended hydraulic cements which meet the requirements of ASTM C595.

The tricalcium aluminate content (C_3A) should not be less than 4 percent to insure durability of the reinforcement. Based on past experience, the maximum tricalcium aluminate content should generally be 10 percent to insure satisfactory durability of the concrete against sulfate attack. The above limits apply to all exposure zones.

Where oil storage is expected, a reduction in the amount of tricalcium aluminate (C_3A) in the cement may be necessary if the oil contains soluble sulfates. If soluble sulfides are present in the oil, coatings or high cement contents should be considered.

Pozzolans conforming to ASTM C618 may be used after tests have been made to indicate improved sulfate resistance and no decrease in corrosion resistance when used in concrete with the planned cement.

Mixing Water

Water for structural concrete or grout should not contain more than 0.07 percent chlorides as Cl by weight of cement nor more than 0.09 percent sulfates as SO_4 when tested by ASTM D512. Chlorides in mix water for prestressed concrete or grout should be limited to 0.04 percent by weight of cement.

Aggregates

Aggregates should conform to the requirements of ASTM C33 or ASTM C330 wherever applicable.

Marine aggregates may be used when conforming to ASTM C33 provided that they have been washed by fresh water so that the total chloride and sulfate content of the concrete mix does not exceed the limits defined in Section 2.8.6 of ACI 718-83.

Concrete

Recommended water-cement ratios and minimum 28-day compressive strengths of concrete for the three exposure zones are given in Table 6.2.

Zone	Maximum W/C Ratio	Minimum 28-Day Cylinder Compressive Strength
Submerged	0.45	5000 psi (35 MPa)
Splash	0.40	5000 psi (35 MPa)
Atmospheric	0.40	5000 psi (35 MPa)

Table 6.2 Water-Cement Ratios and Compressive Strengths for Three Exposure Zones

Measures to minimize cracking in thin sections and to prevent excessive thermal stresses in mass concrete are necessary if more than 700 pounds of cement per cubic yard of concrete are used (415 kg per cubic metre). A minimum cement content of 600 pounds per cubic yard (356 kg per cubic metre) is recommended to insure the quality of the paste adjacent to the reinforcement for corrosion protection.

The rise of temperature in concrete because of cement heat of hydration requires strict control to prevent steep temperature stress gradients and possible thermal cracking of the concrete on subsequent cooling. Reducing the temperature rise may be difficult in the rich mixes and thick sections required in concrete sea structures.

The control of concrete temperatures includes selection of cements which have low heat of hydration, the use of set-retarding admixtures, reduced rates of placement, precooling of the aggregates and water curing. Pozzolans may be used to replace a portion of the cement to lower the heat of hydration.

When freeze-thaw durability is required, the concrete should contain entrained air as recommended by Table 1.43 of "Guide to Durable Concrete" - ACI 201.2R-77.

Where severe scouring action is expected to cause concrete abrasion, the minimum concrete strength shall be increased to 6000 psi (42 MPa). Additional protection can be achieved by using concrete aggregates having equal or higher hardness than the scouring material.

No chlorides should intentionally be added. Total chloride content, as Cl, of the concrete prior to exposure shall not exceed 0.10 percent by weight of the cement for normal reinforced concrete and 0.06 percent by weight of cement for prestressed concrete.

Admixtures

Admixtures should conform to Section 3.6 of ACI 318-83. Limits given in this section for calcium chloride should not increase the total limits recommended for concrete as outlined in Section 2.8.6 of this report (ACI 318-83). When two or more admixtures are used, their compatibility should be documented.

Reinforcing and Prestressing Steel

Reinforcing and prestressing steel should conform to Section 3.5 of ACI 318-77. To facilitate future repairs that might be necessary, only weldable reinforcement should be used in the splash zone. It is to be noted, however, that design criteria for Public Works Canada requires that all reinforcement be spliced.

Post-Tensioning Ducts

Post-tensioning ducts should conform to Section 18.15 of ACI 318-83.

Post-tensioning ducts should be semi-rigid and watertight and at least 1 mm of wall thickness. Ferrous metal ducts or galvanized metal ducts passivated by a chromate wash may be used. Plastic ducts are not recommended.

Bends in ducts should be preformed as necessary. Joints in ducts should be bell and spigot with the ends cut by sawing so as to be free from burrs and dents.

If flexible metal ducts must be used in special areas of congestion, etc., they should have a mandrel inserted during concrete placement. Bars for supporting and holding down such ducts should have a curved bearing plate against the duct to prevent local crushing.

Grout

Grout for bonded tendons should conform to Section 18.16 of ACI 318-83 and to applicable sections of this report. Suitable procedures and/or thixotropic admixtures should be used to prevent pockets caused by bleeding when grouting of vertical tendons or tendons with substantial vertical components.

Recommendations for chloride and sulfate limits for mixing water outlined in Section 2.6 of ACI 357 R-78 also apply to grout mixes.

Admixtures may be used only after sufficient testing to indicate their use would be beneficial and that they are essentially free of chlorides, or any other material which has been shown to be detrimental to the steel or grout.

Concrete Cover of Reinforcement

Recommended nominal concrete covers for reinforcement in heavy concrete walls, 2 in. (50 mm) thick or greater are shown below:

Zone	Reinforcing Steel	Post-Tensioning Ducts
Atmospheric zone not subject to salt spray	2 in. (50 mm)	3 in. (75 mm)
Splash and atmospheric zone subject to salt spray	2.5 in. (65 mm)	3.5 in. (90 mm)
Submerged (50 mm)	2 in. (75 mm)	3 in.
Cover of stirrups may be less than those listed above	½ in. (13 mm)	

Concrete covers of reinforcement should not be significantly greater than prescribed minimums to restrict the width of possible cracks. This would be more critical for those members in flexure.

If possible, structures with sections less than 20 in. (50 cm) thick should have covers as recommended in Section 2.13.1, but when clearances are restricted the following may be used with caution. Cover shall be determined by the maximum requirement listed below:

(a) 1.5 times the nominal maximum size of aggregate, or

(b) 1.5 times the maximum diameter of reinforcement, or

(c) ¾ in. (20 mm) cover to all steel including stirrups.

Note: Tendons and post-tensioning ducts should have 0.5 in. (13 mm) added to the above.

Details of Reinforcement

Reinforcement details should conform to Chapters 7 and 12 of ACI 318-83.

Lapped splices should be avoided in areas of fatigue. However, when lapped splices are used in areas of fatigue, the development length should be two times that computed according to ACI 318-83. Mechanical devices for positive connections should comply with Section 12.15.3.4 of ACI 318-83. Welded splices may be used where reinforcing steel meets the chemical analysis of ASTM A706-76. Public Works Canada design criteria, however, should be consulted for weldment of reinforcing steel.

Anchorages for Embedments

Reinforcing steel bars which are to be welded to embedment plates should be of weldable grade. Welds should be full penetration welds and conform to the American Welding Society "Reinforcing Steel Welding Code" (AWS D12.1).

Epoxy Resins

Epoxy resins may be utilized for waterproofing, sealing construction joints, repairing cracks, and other similar usages. The epoxy resins should be carefully selected on the basis of the materials' suitability for the particular application. Required strength, ability to cure and bond to wet concrete for the temperatures involved should all be considered. Refer to "Use of Epoxy Compounds with Concrete" - ACI 503R-73 and to manufacturers' instructions, along with specialist literature.

6.5 Quality Control Standards

6.5.1 Structural Steel

The magnitude of arctic ice pressures usually require steel structures with thick plate elements which are heavily stiffened. This has resulted in rather severe fabrication problems, especially those due to weld shrinkage and residual stresses. There is also the possibility of lamellar tearing in the presence of large sized welds in thick materials under high restraint. These problems can be controlled by judicious selection of weld procedures and by keeping plate thicknesses down to a reasonable size (say 50 mm or 2"). Pre-heat treatment may be difficult for the particular types of offshore structures involved.

Experience over the past few years has shown that equal attention must be paid to the weldments and to the problems of grain growth in the heat affected zone (HAZ). The question of material was discussed in Section 6.4.1. Materials acceptance standards have been developed in terms of notch toughness criteria which appear to be satisfactory for material quality control. This is not the case for the weld and HAZ. Simply identifying the existence of flaws through non-destructive testing methods is not adequate. What is required, is a procedure which will permit the engineer to define and then to detect flaws of an unacceptable size. There is increasing use of fracture mechanics approaches including the use of the crack-opening displacement test (COD) to define acceptable flaw sizes. This procedure can be used for weldments as well as the parent material. It represents a rational basis for providing better control on fabrication.

The usual non-destructive tests to ensure the quality of welds are:

- Visual Examinations or Inspections to see that there are no visible surface cracks or craters or porosity (gas pockets or voids) and that the weld profiles do not indicate insufficient throat, excessive convexity, excessive undercut and overlap.

- Radiographic or X-ray Examination to detect any subsurface discontinuities or flaws and to ascertain that the dimensions of the flaws, if they exist, are within permissible limits. These flaws or discontinuities could be due to porosity (gas pockets or voids) or due to fusion-type defects (slag inclusion, incomplete fusion, inadequate penetration or other elongated defects). These procedures are entirely for examination of groove welds in butt joints. Inspection of fillet welds by radiographic methods is not recommended.

- Ultrasonic Examination may be used for the same purpose as radiographic examination. This is a more recently developed method and may be used instead of the more traditional radiographic method or to complement it.

- Liquid Dye Penetrant Inspection may be used for detecting discontinuities that are open to the surface.

- Magnetic Particle Examination may be used to detect discontinuities at or close to the surface.

The testing procedures for visual, radiographic and ultrasonic examination are given in CSA W59-1982 "Welded Steel Construction" and the standards of acceptance are indicated in this code.

The Magnetic Particle Inspection is generally carried out in accordance with ASTM Standard E709-80 while the Liquid Penetrant Inspection Method is generally carried out in accordance with ASTM Standard E165-80.

The type and extent of these examinations and inspections will depend on the circumstances and the type of structure. In the case of arctic marine structures where repairs and replacement costs can be very expensive, it is advisable to have an inspection programme as extensive and comprehensive as possible. Initially, the number of tests may be 10% of all welds in the structure, taken from random sampling. If defects are found, the number of tests should be expanded exponentially and may cover 100% of critical portions of the structure.

Recommendations in regard to the welding procedures, workmanship and technique to control distortion and shrinkage in welds are indicated in CSA W59-1982. The "Commentary on Highly Restrained Welded Connections" published by the American Institute of Steel Construction 1973, contains useful information on the detailed design of welds, workmanship and techniques to be adopted to minimize the possibility of lamellar tearing in particular.

Other CSA Standards which may be useful in this connection are:

• CSA W47.1-73	Certification of Companies for Fusion Welding of Steel Structure
• CSA W178-83	Qualification of Welding Inspection Organizations
• CSA W178.2-83	Certification of Welding Inspectors
• CSA W48-83	Arc Welding Electrodes

Crack Opening Displacement (COD) Tests

These tests are performed to define acceptable flaw sizes in the parent material, weldment or HAZ. The procedure is popularly accepted in Europe and Japan and has quite recently been introduced to North America. Generally, the tests are performed in accordance with the British Standard 5762-1979 "Methods for Crack Opening Displacement (COD) Testing".

Test coupons are fabricated from the same material and weldment as the prototype structure and using the same prescribed welding procedure. A tiny saw-cut is introduced into the test coupon to simulate a crack or flaw of a particular size and the test coupon is then subjected to a three-point bending test with the saw-cut on the tension side. The tests are conducted under laboratory conditions which match the service conditions of the actual structure. Values of the crack tip displacement are obtained for various temperatures and strain rates corresponding to actual service conditions. These values will allow for an assessment of the risk of fracture or in other words, whether a particular size of flaw under a certain temperature and strain rate will induce brittle fracture rather than ductile behaviour and at what limiting flaw size will this transition from ductile to brittle behaviour occur.

Since actual cracks and flaws do not follow a simple saw-cut straight-line geometry, correlation between a straight-line and other flaw geometrics must be established to obtain meaningful results in practice. While the COD tests represent a useful tool for quality control, additional work still needs to be done in this regard and the various committees are still working on the recommendations and codification of the COD tests for Arctic Marine steel structures.

6.5.2 Structural Concrete

Quality control during construction of a concrete structure is primarily the responsibility of the Contractor and should be directed by an experienced professional engineer.

All materials to be used in the construction of offshore concrete structures should have documentation demonstrating previous satisfactory performance under similar site conditions or have adequate backup test data.

Testing

Tests of concrete and other materials should be done in accordance with applicable standards of the American Society for Testing and Materials (ASTM) listed in Section 3.8.1 of ACI 318-83. Complete records of these tests should be availale for inspection during construction and should be preserved by the owner during the life of the structure.

Testing in addition to that normally carried out for concrete structures, such as splitting or flexural tensile tests of concrete used in offshore structures may be necessary to determine compliance with specified durability and quality specifications.

6.6 Environmental Aspects

6.6.1 Land Use Regulations

For any arctic project the following documents should be consulted:

> "Land Use Guidelines, Mineral Exploration - Yukon and Northwest Territories" 1983 - Volume 2, Appendix 1. Provides guidelines for Environmental Protection and Minimizing Environmental Damage.
>
> "A Guide to Territorial Land Use Regulations" 1981. Provides answers to questions regarding the "Territorial Land Use Regulations" and information on how they are administered. Refer to Volume 2, Appendix 1 for details of these particulars.
>
> "Northern Natural Resource Development: Requirement Procedures and Legislation" 1981 - Volume 2, Appendix 1. This publication identifies various licences, permits or other types of authorization required for any construction project. It provides a detailed explanation of the types of authorizations and procedures involved when an application is made and the various organizations that are involved in authorizing the application. It directs the user to the various acts and regulations of the Department of Indian Affairs and Northern Development.

6.6.2 Environmental Guidelines

Details of environmental phenomena which may influence the design of arctic marine structures are identified in Paragraphs 1.3 - Environmental Data, and 1.5 - Selecting the Design Environmental Conditions in API RP 2A (1981).

Statistical methods are generally used to describe environmental parameters. The seasonal and yearly variations of environmental phenomena such as wind, waves, currents, and ice features may be described by statistical distributions appropriate to the environmental parameters and environmental data considered.

In the assessment of extreme values, recognized extrapolation techniques should be used.

6.6.2.1 Specific Environmental Conditions

Existing regulations and guidelines relating to environmental factors in the arctic are as follows:

Wind

Wind profiles over ice will be different from those over open water due to the rough shape of the ice surface. The possibility of channelling of wind between ice features should also be considered for each type of structure. API RP2A (1981), Paragraph 1.3.2, Winds, provides a general discussion on winds.

For open water, wind velocity profiles such as provided in API RP 2A (1981), Paragraph 2.3.2, Wind, may be used.

For ice covered areas, the wind velocity profile for open water may require modifiction. One example is provided by Leavitt (1978 - Volume 2, Appendix 2).

Wind Velocities

The Climatic Atlas (1977 - Volume 2, Appendix 1) is an example reference useful in the selection of normal wind velocities. Acceptable analytical methods should be used for the determination of extreme wind velocities.

Temperature

The Climatic Atlas (1977 - Volume 2, Appendix 1) is a useful reference for use in the selection of normal and extreme temperatures. The apparent air temperature as a function of wind speed should be considered when determining worker safety and comfort.

Precipitation

The amount of precipitation from rain, snow, and freezing rain should be determined to describe the environment and to calculate the loads on roofs and large horizontal surfaces. The effects of snow accumulation and its insulating effects should be accounted for when determining the depth of frost penetration and ice thickness. Data on precipitation may be found in the Climatic Atlas (1977 - Volume 2, Appendix 1).

Visibility

Visibility is important for safe helicopter and supply operations. Poor visibility may result from ice fog or snow whiteouts (e.g. blowing snow with low contrast lighting). Data on visibility may be found in the Climatic Atlas (1977 - Volume 2, Appendix 1).

Superstructure Icing

Icing of structural members can result from fog or wind driven sea-water spray. Icing may affect the safety of vessels during on-site construction and supply operations. Data on icing may be found in the Climatic Atlas (1977 - Volume 2, Appendix 1).

Wave Parameter Guidelines

Wave parameter guidelines for normal sea states may be found in the Climatic Atlas (1977 - Volume 2, Appendix 1).

Currents

API RP 2A (1981 - Volume 2, Appendix 1), Paragraph 2.3.3, Current, presents an approach for calculating current variations with depth in the absence of waves and for currents associated with waves.

Tide and Storm Surge

The changes in sea surface elevation from tides and storm surges need to be considered in describing the environment. The superposition of astronomical and storm surge tides, for example, may be justified to determine deck elevations to prevent wave slamming. Minimum sea surface elevations may also be of engineering significance and should be based on the astronomical tides and, where appropriate, the negative storm surges.

The best source of tidal information is from direct measures at the site. If data directly applicable to the site are not available, the best estimate based on data for nearby locations may be acceptable. Some data may be found in the Climatic Atlas (1977 - Volume 2, Appendix 1).

CHAPTER 7

DESIGN GUIDELINES

7. DESIGN GUIDELINES

Many of the current codes of practice such as API Bulletin RP2A-1981 "Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms", the DnV "Rules for the Design, Construction and Inspection of Offshore Structures" (1977) and the ACI 357 R-78 "Guide for the Design and Construction of Fixed Offshore Concrete Structures" (1981) contain design guidelines which are applicable to Arctic marine structures. Where appropriate, a selection of these guidelines are reproduced in this Handbook to assist the Planner and/or Engineer.

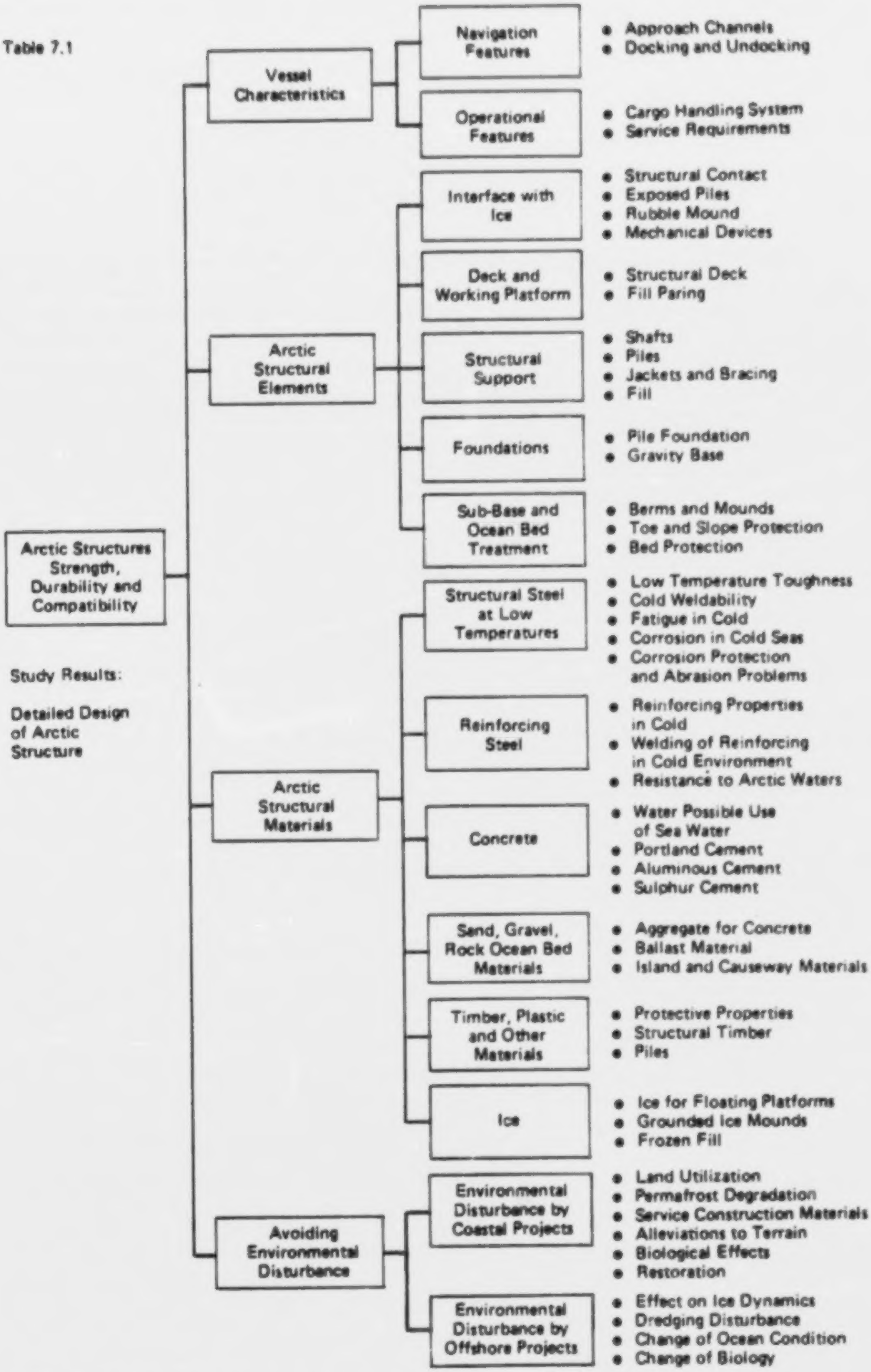
7.1 Functional Planning

Functional planning of Arctic marine structures vis-a-vis vessels and operating environment must consider the following factors:

Site Selection	- existing environmental conditions
	- geotechnical features
	- environmental impact of project
	- navigation aspects
	- design aspects
	- construction feasibility
Master Plan and Alternative Layouts	- environmental impact
	- geotechnical variations
	- vessel characteristics
	- major civil structures
	- operational feasibility
	- construction factors
	- capital and operating cost parameters
Marine Structure Selection	- environmental conditions
	- geotechnical conditions
	- vessel characteristics
	- design features
	- construction feasibility
	- capital and operating costs factors

Illustrated in Table 7.1 is a logic diagram which may be used as a general guideline in preparation of the design of an arctic marine structure.

Table 7.1


Arctic Structures Strength, Durability and Compatibility
Vessel Characteristics
Navigation Features
• Approach Channels
• Docking and Undocking
Operational Features
• Cargo Handling System
• Service Requirements
Arctic Structural Elements
Interface with Ice
• Structural Contact
• Exposed Piles
• Rubble Mound
• Mechanical Devices
Deck and Working Platform
• Structural Deck
• Fill Paring
Structural Support
• Shafts
• Piles
• Jackets and Bracing
• Fill
Foundations
• Pile Foundation
• Gravity Base
Sub-Base and Ocean Bed Treatment
• Berms and Mounds
• Toe and Slope Protection
• Bed Protection
Arctic Structural Materials
Structural Steel at Low Temperatures
• Low Temperature Toughness
• Cold Weldability
• Fatigue in Cold
• Corrosion in Cold Seas
• Corrosion Protection and Abrasion Problems
Reinforcing Steel
• Reinforcing Properties in Cold
• Welding of Reinforcing in Cold Environment
• Resistance to Arctic Waters
Concrete
• Water Possible Use of Sea Water
• Portland Cement
• Aluminous Cement
• Sulphur Cement
Sand, Gravel, Rock Ocean Bed Materials
• Aggregate for Concrete
• Ballast Material
• Island and Causeway Materials
Timber, Plastic and Other Materials
• Protective Properties
• Structural Timber
• Piles
Ice
• Ice for Floating Platforms
• Grounded Ice Mounds
• Frozen Fill
Avoiding Environmental Disturbance
Environmental Disturbance by Coastal Projects
• Land Utilization
• Permafrost Degradation
• Service Construction Materials
• Alleviations to Terrain
• Biological Effects
• Restoration
Environmental Disturbance by Offshore Projects
• Effect on Ice Dynamics
• Dredging Disturbance
• Change of Ocean Condition
• Change of Biology

Study Results:

Detailed Design of Arctic Structure

Table 7.1 Logic Diagram for the Preparation of Detailed Design of Arctic Structures

7.2 Environmental Loads

The purpose of this section is to identify the present state-of-the-art evaluation of environmental loads applicable to marine structures.

Although many environmental loads applied to arctic marine structures are similar to non arctic structures, it is a fact that ice related loads predominate. Loads on structures caused by wave or current action may be affected by ice in one form or another.

In order to provide a complete picture of environmental loads on an arctic marine structure, a review of all significant environmental loads which must be considered is presented herewith.

Relevant references are provided for the theoretical or empirical derivations of concepts discussed. It is suggested that the user of this Handbook familiarize himself with the appropriate references before applying the guidelines indicated herein.

7.2.1 Wave

Wave loads on offshore structures are generally predicted by a semi-empirical approach. The derivatives of a theoretically derived flow potential function are combined with empirical drag and inertia coefficients to predict wave-forces on structural components relative to the position of the wave. By considering the proper phase angles between the two force components, the maximum wave load can be obtained by algebraic summation of the force components.

A background on the selection of applicable flow potential function is given in "Estuary and Coastline Hydrodynamics" by A.T. Ippen, McGraw-Hill, New York, 1968. Water depth, wave height, and wave period in a specific geographical region are the most important parameters for the selection of an appropriate flow potential function.

Drag and inertia coefficients are experimentally derived. API Bulletin RP2A suggests the typical values for cylindrical members will range from 0.6 to 1.0 for the drag coefficient C_D and from 1.5 to 2.0 for the inertia coefficient C_M.

For small diameter cylindrical members such as piles and bracings, having member diameter to wave length ratio or $D/L < 0.2$, the Morison equation is generally applicable. (Reference: Morison J.R. et al., "The Force Exerted by Surface Waves on Piles", Petroleum Transactions, AIME, 1950).

With increasing member sizes the inertia forces become dominant. The variation of the value C_M with the D/L ratio may be obtained from

"Handbook of Ocean and Underwater Engineering" edited by J. Myers, McGraw-Hill, 1969.

Rapidly decreasing values for C_M indicate that wave scatter is becoming significant.

For large diameter obstructions such as caissons where the D/L ratio may exceed 0.2, wave diffraction becomes significant and the Morison equation can no longer be applied. For this condition, the method recommended by R.C. McCamy and R.A. Fuchs ("Wave Forces on Piles: A Diffraction Theory" Technical Memo No. 69, Beach Erosion Board, US Army Corps of Engineers, 1954 - Volume 2, Appendix 2) may be applicable. For very large cylindrical obstructions having diameters comparable with the wave length, the method by R. Bonnefille ("The Action of Waves Upon Large Isolated Cylindrical Structures", Bulletin No. 3 du Centre de Recherches et D'essais de Chaton, France, 1963) may be applicable.

The maximum adopted design wave for the design of the wharf structure is usually the extreme wave. For detail discussion, refer to Section 2.3.5.

A dynamic analysis of the structure should also be carried out to determine whether significant wave force amplication can be expected. The method proposed by N.M. Newmark ("The Effect of Dynamic Loads on Offshore Structures", Proceedings of 8th Texas Conference on Soil Mechanics and Foundation Engineering, 1956) may be applicable.

7.2.2 Current

The current velocity selected for design should be determined by appropriate means. In the absence of more detailed information, the variation of current velocity with water depth may be estimated from guidelines presented in API Bulletin RP 2A.

While the current loads will usually be small compared with other environmental loads and will unlikely govern the structural design, secondary effects such as foundation scour and current-flutter due to vortex shedding may be important enough to warrant detailed investigations.

Currents may be a significant operational factor for vessels and should be taken into consideration when the wharf alignment is being selected.

7.2.3 Wind

Wind pressures applicable to the design of marine structures in the Canadian arctic is given in the National Building Code of Canada

Supplement No. 4, 1980. The velocity selected should be consistent with the risk assumed for the structure.

While wind loads will not generally govern the design of the substructure, they may control the design of some superstructure elements located above deck. They will have an impact on wharf operations and site specific information must be utilized in selecting wharf alignment.

7.2.4 Ice

The prediction of ice-load on arctic marine structures require meteorological data concerning the presence and characteristics of ice for a specific region coupled with information identifying the different modes of ice formation to be expected (i.e. first year ice, multi-year ice, consolidated and unconsolidated ice ridges, ice islands, icebergs, etc.). From this extreme environmental event, a design ice-feature is selected which the structure must resist. This is the deterministic approach.

Reference should be made to Chapters 2.0 and 3.0 of this handbook for a detailed review of this subject.

Alternatively, a probabilistic approach may be used which takes into account such variables as the probability distribution of ice ridges or the histogram of kinetic energy of icebergs for the risk/safety analysis of the structure. In this connection, reference may be made to the following papers:

- Ian J. Jordan, "Risk and Safety Assessment for Arctic Offshore Projects", Proceedings of 2nd Annual MIT Sea Grant College Program Lecture and Seminar, 1983 - Volume 2, Page 20;
- W.D. Hibler, "Statistical Variations in Arctic Sea Ice Ridging and Deformation Rates", Proceedings Ice Tech. Symposium, Montreal, 1975 - Volume 2, Appendix 2;
- J.D. Wheeler, "Probability Distributions for Structure Loading by Multiyear Ice Floes", Proceeding 6th International Conference POAC, 1981 - Volume 2, Page 45.

The predicted ice loads as developed, will depend on the ice structure interaction which for a selected ice design criteria will depend on the geometry, size and flexibility of the structure as well as the rate of loading. The geometry of the structure will also determine the mode of failure of the ice. For instance, vertical faced tower like structures such as piles, piers, or caissons will cause the ice to fail by indentation or crushing whereas cone-faced structures may cause ice to fail by flexure or bending. The size or width of the structure determines the aspect ratio which is structure width divided by ice thickness. For narrow indentors or small aspect ratios, the effective ice pressure may be several times larger than the uniaxial compression strength of the ice (V.P. Afanas'ev "Ice Pressure on Vertical Structures", Transportnoe Stroitel'stvo, 1972 - Volume 2, Appendix 2).

A cone-shaped structure tends to induce flexural failure in the ice-sheet and so result in substantially lower loads on the structure. The total ice load on the structure in this case is not only the rupture load of the intact ice-sheet but must include the ride up load or work which is done by broken ice pieces which ride up and around the structure. (T.D. Ralston "Plastic Limit Analysis of Sheet Ice Loads on Conical Structures", Intern. Union of Theoretical and Applied Mech. Symp. on Physics and Mechanics of Ice, Copenhagen, 1979 - Volume 2, Appendix 2. Also, "Ice Force Design Considerations for Conical Offshore Structures", 4th Intern. Conf. on POAC, 1977 - Volume 2, Page 122). The sea is not necessarily in continuous motion. It is possible therefore for broken ice and the surrounding ice-sheet to become frozen to the structure during a quiet period. This phenomena of "adfreeze" can defeat the purpose of using a cone-shaped structure to induce flexural failure. The adfreeze bond must be broken before other failure modes can be induced. Adfreeze can be avoided by providing heat tracing to the structure or can be substantially reduced by the use of special coatings.

The presence of ice ridges will substantially increase the ice loads on the structure compared to those exerted by the ice-sheet alone. In this regard field measurements in Cooke Inlet on 14 feet diameter cylinders over a period of 2 years indicate that the load from a ridge may be from 1.5 to 3.6 times the load from the parent sheet alone. Predominant values varied between 2.0 and 2.5. Based on this data, an empirical "ridge factor" of 2.0 to 2.5 is sometimes used to account for pressure ridges. Alternatively, a probabilistic approach may be used to assess the risk/safety of the structure if sufficient data on the sizes and geometry of ridges are available for the area.

The flexibility/rigidity of the structure will influence the actual magnitude of ice load experienced by the structure. It has been shown by Määttänen that a flexible or compliant structure will experience lower ice forces compared to a more rigid structure ("Ice Forces on Fixed Flexible Structures", IAHR, 1980 - Volume 2, Appendix 2).

The loading rate or strain rate will also influence the magnitude of the ice loads. It is well known that the strength of ice is low for very low strain rates because of the visco-elastic nature of ice. With increasing strain rates the ice strength increases but only up to a certain peak or plateau, after which the ice strength will no longer increase with strain rate. This maximum peak strength is attained at a strain rate of about 10^{-3} per second (Exxon 1979 - Volume 2, Appendix 2). Other factors that affect ice strength are temperature, brine-content, crystal type and the direction of loading.

For large sized structures or wide indentors such as large caissons, platforms or islands, the effective ice pressure is generally lowered due to non-simultaneous failure of ice-sheet over the wide contact area when considered as a number of loaded strips or channels (P.R. Kry "Ice Forces on Wide Structures", Proc. Canadian Geotechnical Journal, Feb. 1980 - Volume 2, Page 51).

For offshore island platforms or causeway type structures, the method suggested by Vivatrat and Kreider ("Ice Force Prediction Using a Limited Driving Force Approach" OTC 4115, 1981 - Volume 2, Appendix 2) may be applicable.

For piled structures in tidal waters, there is also the possibility of uplift forces on the piles generated by adhesion of the ice-sheet around the piles and lifting by a rising tide. Design recommendations by M. Määttänen ("Design of Navigational Structures for Ice Forces", ASCE, 1983 - Volume 2, Appendix 2) may be applicable.

For dams and lock walls subjected to static forces from thermal movements of an ice-sheet, Canadian practice has been to use an ice force of 10 to 15 kips/linear foot. This criteria should not be used for an isolated pier frozen into a large ice-sheet. For this condition, it has been suggested that the above ice force be applied to a length equal to the pier width plus 1/3 of the clear span of the opening between piers.

Dynamic forces involving ice crushing or bending fracture are usually accompanied by force oscillations arising from the mode of fracture which tend to induce vibrations in the structure. Dynamic amplification should be assessed where applicable using Newmark's method ("The Effect of Dynamic Loads on Offshore Structures", Proc. of 8th Texas Conf. on Soil Mech. and Foundation Engineering, 1956 - Volume 2, Appendix 2) or other suitable methods.

For more detailed information on the ice structure interaction and the ice pressure algorithm applicable to design of various structure types, reference is made to Sections 3.6 and 3.7 of this handbook.

The resultant ice forces selected for structural design should include both global as well as local ice pressures.

7.2.5 Seismic

The level of seismic accelerations to be expected at various locations in the Canadian Arctic are indicated in the seismic map in Supplement No. 4 of the National Building Code of Canada. Reference should be made to Section 4.1.5 of this Handbook. The design approach taken for the seismic design of arctic marine structures is to design the structure to respond without damage to a selected design event and then to check that this design will enable the structure to survive the conditions of the extreme earthquake, albeit with some damage.

The design procedure will generally involve the following steps:

- Seismicity study of the site with its seismic history and local geography.

- Site response studies involving the local soil conditions and foundation material.

- Selection of Design Criteria involving the definition of the design level earthquake and the survivability level earthquake.

- Dynamic analysis involving structure soil, structure fluid and structure ice interaction during an earthquake.

- Stress analysis involving the output of stresses in various structural components.

- Evaluation of various failure modes involving both global and local stress effects, and the possibility of progressive collapse.

- Satisfying ductility requirements involving the development of seismic structural details. This is particularly important for concrete structures since concrete material is brittle per se and structural ductility can only be obtained by appropriate detailing of steel reinforcement.

For seismic design of steel structures, detailed procedures and criteria are contained in the API Bulletin RP2A. For concrete structures, further reference may be made to ACI 357R-78.

7.3 Conceptual Design

In general, the conceptual design of an arctic marine structure should take into account the following inter-related parameters:

- Sea Approach and Exit - should be direct with minimum turning requirements for docking and undocking procedures.

- Water Depth - to accommodate design vessel. Dredging should be avoided as far as possible.

- Space and Service Requirements - to accommodate buildings, equipment and personnel. Support services such as water, power, fuel and lighting must be provided considering arctic environment.

- Ice Effects - as they affect structures and navigability. Space must be provided at wharf face between structural elements to clear ice from berthing area.

- Wind Effects - as they affect vessels and wharf operations. Wharf should be aligned parallel to prevailing wind where possible.

- Wave Effects - as they affect erosion, spray, superstructure icing, overtopping and structural impact.

- Current Effects - as they affect vessel movement and scour on foundation system.

- Foundation Conditions - as they affect sea bottom support system. Must be adequate to provide stability against anticipated ice forces.

- Geotechnical Stability - to ascertain that there are no major faults and the soil is not subject to liquification in an earthquake. Also, to ensure that construction process will not adversely affect geotechnical conditions.

- Structure Response to Loadings - to ensure a safe response at the operating as well as shut-down or evacuation levels.

- Available Construction Materials - to ensure that the construction materials selected are readily and economically available.

- Availability of Equipment and Techniques - to ensure that the construction methodology envisaged can be accomplished by available equipment and construction techniques.

For the case of steel or concrete structures designed to be built in the south and transported to the north, the draft and stability in the floating mode is critical, as is the set-down operation.

7.4 Selection of Alternatives

Arctic marine terminal sites are remote and generally have severe ice conditions. The choice of basic structural systems is therefore limited. To date, most wharves constructed in the Canadian Arctic have taken the form of large diameter cells connected to shore by causeways. The Asbestos Corporation Ltd. wharf at Deception Bay was the first to utilize large diameter steel sheet pile cells in the Canadian Arctic. The cells were built during the ice free period using conventional constructional methodology. Ice based construction was not considered feasible due to high tides at the site. This facility was designed in 1971.

In 1975, a similar type of design was utilized for the Strathcona Sound Marine Terminal at Baffin Bay for Nanisivik Mines Ltd. In 1981, steel sheet pile cells were again used for the Cominco Wharf at Little Cornwallis Island. Steel sheet pile cells were also proposed for the Melville Island LNG terminal at Bridport Inlet in 1980. Where site conditions permit, the cells were constructed during the winter period using the ice as a working platform. The approach causeways were constructed using conventional earth-moving equipment.

The choice of steel sheet pile cells was made recognizing that this type of structure can be built to withstand large ice forces and are suitable for arctic construction, using simple techniques and standard construction equipment. These reasons are still valid today in the selection of this preferred design alternative for the Canadian Arctic.

Large diameter reinforced concrete cells or caissons were used for the Golden Eagle Oil Wharf at Hadlow Cove, on the St. Lawrence River (Volume 2, Page 296). Although this is not an arctic site, ice conditions are extremely severe and represent arctic type environmental loading. Some of the cells act as ice-breaker cells and were designed to resist the very large ice forces present at that site. This type of structure was selected because site conditions favoured a floated in gravity structure and construction facilities were locally available for the building, launching and setting of concrete cells.

In more benign ice conditions, conventional piled foundations may be used for the wharf sub-structure, as was adopted in some locations in Alaska. However, wharf pile structures have a number of failures recorded under various ice conditions and this type of structure should only be adopted with careful consideration of environmental factors.

7.5 Design Principles

Design principles currently utilized for arctic marine structures, are presented and discussed to highlight those features which are most critical to effective design.

7.5.1 Codes and Rules

Depending on the structure type, the design of an arctic marine structure may be carried out to conform to one or more of the existing codes of practice. Reference should be made to Chapter 6 of this Handbook.

7.5.1.1 Steel Structures

There is at present, no single design code which adequately addresses the design of arctic marine structures. Codes in general use are as follows:

• API Bulletin 2N (1981)	"Planning, Designing and Construction of of Fixed Offshore Structures in Ice Environments"

• ABS (1983)	"Rules for Fixed Offshore Structures" (currently under revision to include Arctic applications)
• CASPPR (1979)	"Arctic Shipping Pollution Prevention Regulations"
• Dn V (1977)	"Rules for the Design, Construction and Inspection of Offshore Structures"
• AISC (1980)	"Manual of Steel Construction"
• CSA-S16 (1980)	"Steel Structures for Buildings"
• AWS D.1 (1979)	"Structural Steel Welding Code"
• CSA W59 (1982)	"Welded Steel Construction"

7.5.1.2 Concrete Structures

• ACI-357 R-78	"Guide for the Design and Construction of Fixed Offshore Concrete Structures" (currently under revision to include Arctic applications)
• FIP (1980)	"Recommendations for Concrete Sea Structures" (4th Edition in preparation to include Arctic applications)
• Dn V (1977)	"Rules for the Design, Construction and Inspection of Offshore Structures"

7.5.1.2 Concrete Structures

Reference may be made to Section 6.3 for Structural Codes and Standards, Section 6.4 for Material Standards and Section 6.5 for Quality Control Standards.

7.5.2 Design Methodology

As noted previously, the predominant load on arctic marine structures, as compared to non-arctic conditions, is from ice forces due to ice packs or floes moving against the structure and icing of the structure. Information concerning the causes and development of these forces are presented in Chapter 3.0.

This section describes the design methodology for selected arctic marine structures against ice loads. Design against other environmental loads, have been summarized under Sections 7.2 and 7.3.

The design of arctic marine structures is discussed under four major classifications:

- causeway or breakwater structures
- gravity structures
- structural systems
- floating structures

7.5.2.1 Causeway/Breakwater Structures

The planning and design of rubblemound structures for use in the arctic involves a broad range of factors including not only wave and ice conditions, but also very severe constraints on construction schedules, material supply and economy. These factors are summarized in following Tables 7.2 and 7.3.

In overview, functional design issues can be divided into geometrical design (for management of ice structure interaction) and armor design (for maintaining the geometry selected). Each structure must be carefully examined to determine how ice is to be accommodated in the design and how to best provide the necessary armor protection. Generalized guidelines for such a design selection scheme are presented as follows:

It is clear that there are numerous solutions to the problem of rubble mound structures in the arctic. The various alternative combinations of geometry and armor type are appropriate depending upon site and functional requirements to be accommodated, such as wave intensity and ice regime as well as the service life of the structure. By virtue of the generalized approach in AOGA Project #126, there is now available more recent and specific engineering knowledge applicable to arctic marine structure design.

Reference may be made to the paper "Design Factors for Rubble Mound Structures Under Ice and Wave Attack" by M.T. Czerniak, A.T. Shak and J.I. Collins (POAC, 1981 - Volume 2, Page 9) from which the information in this section has been synthesized.

Ice Pileup/Rideup/Overtopping

Ice pileup commonly occurs on arctic beaches when advancing ice sheets fail near the coast in a manner that causes piles of ice rubble to form. The occurrence of a pileup essentially prevents ice from advancing further onto the beach. In an ice rideup event, combinations of ice characteristics and shore characteristics are such that the ice, though failed into blocks, gets pushed inland overriding the underlying surface. Events of ice rideup are potentially destructive to backshore features or nearby manmade structures. Ice overtopping is a term that can be used to describe ice which topples over a retaining device after pileup in much the same way that waves overtop a structure.

Kovacs and Sodhi (1979, 1980 - Volume 2, Appendix 2) have examined the historic occurrences of ice pileup and rideup, and the physi-

A. Design Factors

1. Wave Conditions
    - Degree of exposure
    - Normal and storm wave characteristics
    - Water depth-breaking wave conditions
    - Variations during tide
    - Variations during storm water level setup or setdown conditions
2. Ice Conditions
    - Sea ice conditions and movement
    - Floating ice fragment conditions and movement
    - Grounded ice conditions - ridges
    - Ice characteristics and pressures
3. Water Depth Considerations
    - Effect on fill requirements
    - Distance offshore - construction techniques
4. Water Level Conditions
    - Tide range
    - Storm setup and setdown
5. Current Conditions
    - Hydrodynamic forces
    - Construction considerations
    - Scour considerations
    - Effect on ice conditions

B. Construction Factors

1. Viable Construction Methods
    - Expertise required
    - Time required
    - Equipment required
    - Duration of construction season
    - Extreme weather downtime during construction season
    - Mobilization factors
    - Cold weather construction implications on manpower, equipment and materials
2. Construction Materials Available
    - Quantity
    - Quality
    - Distance and difficulty of transport
    - Types (rock, sand, gravel, concrete, etc.)
    - Access routes

C. Cost Factors

1. First Cost
    - Manpower - skill levels and amount
    - Equipment - mobilization; operations; demobilization
    - Materials
    - Cost vs economic benefit of structure
2. Maintenance Considerations
    - Risk vs convenience (allowable damage vs overdesign)
    - Intended service life of structure
    - Future cost of manpower, equipment and materials
    - Equipment availability once demobilized

D. Regulatory Considerations

- Applicable Federal, State and local ordinances, stipulations, CZM guidelines, etc.
- Allowable construction techniques
- Allowable operational seasons
- Removal and restoration requirements
- Environmental impacts - physical, biological, sociological

Table 7.2 Perspective: Planning Consideration for Rubblemound Structures in Cold Regions

A. Wave-Structure Interaction

  1. Cross-Section Design

     - Geometry-wave runup and overtopping
     - Slope-wave runup and fill quantity factors
     - Dimensions for functional useage of structure
     - Elevation-overtopping considerations
     - Backslope drainage features
     - Ease of construction and maintenance

  2. Stability Design

     - Armor type, placement, size, and density
     - Armor porosity
     - Armor slope
     - Crest stability design-overtopping aprons
     - Toe stability design
     - Underlayer considerations
     - Tradeoffs with ease and cost of construction and maintenance
     - Damage sensitivity-failure modes
     - Service life and maintenance philosophy

B. Ice-Structure Interaction

  1. Cross-Section Design

     - Geometry as relates to ice rideup and pileup events
     - Structure slope and volume requirements to resist ice loading
     - Crest configuration for ice overtopping design
     - Ice pileup storage considerations
     - Ease of construction and maintenance
     - Effect of ice foot and adfreeze on ice pileup and rideup

  2. Stability Design

     - Local slope failure-freeze front and geotechnical factors
     - Armor displacements by ice sheet
     - Armor displacements by ice fragment impact
     - Armor displacements by plucking
     - Armor breakage
     - Effect of adfreeze and ice foot
     - Armor or toe gouging by ice ridge grounding
     - Crest stability during ice pileup-rideup events
     - Tradeoffs with ease and cost of construction and maintenance
     - Underlayer considerations
     - Damage sensitivity-failure modes
     - Service life and maintenance philosophy

C. Construction and Operational Scenario

  1. Construction Stage

     - Floating construction
     - Land-based construction
     - Over-ice construction
     - Length of construction season and season extension techniques
     - Storms during construction
     - Armor and underlayer fabrication
     - Fill-first construction techniques
     - Fill retaining construction techniques
     - Stages construction

  2. Operational Stage

     - Functional downtime vs various wave, water and ice events
     - Periodic maintenance and inspection
     - Snow and ice clearing
     - Operational season vs year-round operation

Table 7.3 Focus: Design Factors for Rubblemound Structures in Cold Regions

cal factors governing their occurrence. They point out that Taylor (1977) observed an ice rideup scar that extended 185 metres inland from the shoreline along Somerset Island on the Canadian Beaufort coast. Observations show that the period of pileup or rideup may be of short duration, less than 30 minutes, and can occur any time of the year but more frequently in the Fall and Spring, during freeze up and break up, when ice is most mobile. Tsang (1975 - Volume 2, Appendix 2) reports on a witnessed ice pileup event on a Canadian lake during which ice piled to a height of about 2 metres above lake level in thirteen minutes. The ice pileup-rideup events summarized by Kovacs and Sodhi (1979, 1980) contain several references to very large ice encroachments on beaches, on structures, and up and over fluggs.

It should be noted that ice rideup or pileup will occur only when a structure is directly subject to large scale movements of level ice. Ridges which ground on the structure slope will effectively block the structure from further attack by level ice and therefore to ice rideup or pileup. Previous pileups act in much the same manner in that subsequent pileups will likely occur seaward of the original pileup.

It is established from reported historical evidence that rideup/pileup/overtopping must be considered in rubble mound structure design. For structures that are used only during the ice free season, such as loading or unloading causeways at arctic ports, it may be permissible to allow rideup to occur. This approach has been recently used in the design of a causeway to serve the expanded Port of Nome. At least for the foreseeable future, the causeway will be used only in ice free seasons for vessel loading and unloading. In this design, all critical utility services and pipelines are located in a utilidor below the surface of the causeway to permit winter ice rideup to go over the top. Later, if winter operations are desired, the structure can be altered to include rideup prevention features.

For structures that will be used or occupied during the winter, it is necessary to induce ice pileup at the perimeter of the structure so that ice can not invade the working surface. Literature, field observations, and laboratory tests indicate that ice pileup may be induced by sharp breaks in slope geometry, by slope roughness sufficient to cause the advancing ice sheet to fail and induce a pileup, or by a combination of slope geometry and slope roughness.

Croasdale et al. (1978 - Volume 2, Appendix 2) suggested breaks in slope and jam features to induce ice piling. A break in slope from a steep to flatter slope induces a pileup at the apex of this slope by flexural failure. An extension of this concept is a horizontal berm in the slope profile which is used to accommodate the ice pile. Such berms have been used for riverine ice environments (Danys 1979 - Volume 2, Appendix 2), and in Sounds (Brunn and Johanesson 1971 - Volume 2, Appendix 2). A jam feature, or break in slope from a flat to a steeper slope is thought to induce ice piling by bending, crushing or buckling. Both features can be included by using a berm lower on the structure profile and a jam feature higher on the profile. In the case of the Port of Nome, should port operations be expanded to include winter operations, the causeway can be altered by building a low bench on the seaward side of the profile which will result in an overall profile with berm and jam features.

Another geometry which will resist ice rideup is the steep-sided or vertical-sided structure. Brunn and Johannesson (1971 - Volume 2, Appendix 2) studied ice rideup along coastal structures and concluded that vertical walls do not favor ice rideup if the toe depth is greater than some "critical depth". It can be inferred from their paper that the value of this "critical depth" is greater than 5 metres. Observations of rideup on ice islands grounded in over 10 metres of water in the Beaufort Sea indicate that the "critical depth" concept is not the only factor determining whether or not ice override will occur upon meeting vertical faces. Grounded ice island fragments typically have vertical walls and a freeboard of three to four metres. It is noted that the existence of a critical depth is probably a function of ice thickness, strength, orientation to wall, direction and magnitude of ice movement, velocity, integrity of the ice floe, and other factors. It is clear, however, that a vertical face of some height is effective in preventing ice rideup.

The volume of ice to be accommodated as a pile on the structure is related both to the design event of ice movement and whether the ice piles landward or seaward once piling starts. It should be remembered that ice encroachment on to the structure will happen only if a previous pileup did not occur, or if a grounded ridge does not prevent the level ice sheet from impinging directly on the structure. Given such a clear "shot" at the structure, the volume of ice in one event is related to the intensity, duration, and direction relative to the structure of the forces moving the ice sheet.

Since winds seem to cause the largest movement of ice sheets, the design event is the joint probability of wind speed, wind direction, wind duration, and the lack of previous pileups or grounded ridges on the structure. Without these statistics, an "extreme" design event can be selected on the basis of the longest documented or expected ice sheet movement.

Once design features induce pileup, the piling process and the pile itself are the next elements of design concern. Ice piling on coastal structures has been described by Brunn and Johannesson (1977 - Volume 2, Appendix 2) to heights of ten metres above the still water level. Kovacs (APOA Project #89-1975) reports measured ice pileups as high as about 14 metres on an exposed portion of Banks Island in the Canadian Beaufort when the offshore ice was about 7 feet thick. Ice pileups have been estimated as high as 100 feet. In the Alaskan Beaufort, ice pileups observed on Cross and Narwhal Islands had mean heights and peak heights in excess of seven metres and 12 metres, respectively. Ice pileups also reached to 23 metres above sea level against the cliffs at Barrow, Alaska (Kovacs and Sodhi 1979, 1980). Kovacs and Sodhi describe the ice piling process on flat beaches as proceeding generally seaward after the pile apex forms over the shoreline. By using pile height, a 30° side slope (Kovacs and Sodhi 1979, 1980), and the apex position, the design volume of ice can be accommodated in the design. There is some laboratory evidence that on smooth steep slopes with a thick and fairly strong ice sheet, the original pile may be submarined by the advancing ice sheet, causing the pile to grow landward instead of seaward. However, thick ice sheets move only in Spring near breakup when they are usually weak. Thus, this event in nature would seem to be rather unlikely. Of course different slope geometries will accommodate different volumes of ice in "storage" on the structure. It may be necessary to clear ice pileups from the structure if it "fills in" the slope geometry. Otherwise the next advancing ice sheet may see only a constant slope and not the slope break or jam features.

Slope roughness can also be considered as a way to induce ice pileup. As the advancing ice sheet accommodates roughness, its leading edge is retarded while the driving force continues, leading to a buckling/bending failure, which induces a pileup. Again some maintenance or clearing operations might be in order because a subsequent ice movement may ride over the previous ice, thus rendering the slope roughness ineffective. The size of the roughness feature relative to the ice thickness would seem important or bridging over the armor units would effectively cancel the roughness. However, the degree of roughness or smoothness presented by the armor units is also a concern in causing local slope failures described below. Another scheme is to use "tank traps" or "parapets" (Vaudrey and Potter 1981 - Volume 2, Appendix 2) which present both a projection from the surrounding surface (roughness) and the opportunity for bending failure in two directions.

Ice overtopping is easily accommodated in the design by allowing a buffer zone for the ice chunks. Anything damaged by falling ice should not be placed within the buffer zone. The volume of overtopping ice must be accommodated in order to keep it from spilling onto the work surface of the structure.

Displacement of Armor Units

Displacement failure of the armor layer under ice action can occur by "bulldozing" during ice push or "plucking" when the ice freezes around armor units and then retreats away from the island. There is no directly applicable experience recorded which would indicate how various armor units interact with intensive ice conditions such as those found in the Beaufort Sea. However, some insight may be gained from the following reports.

Studies of naturally occurring boulder pavements subjected to ice floes along the Mackenzie River showed that some boulder pavements are remarkably stable, and may persist for a century or more. These pavements were characteristically composed of boulders tightly pressed into stony river muds with a preferred boulder long axis orientation parallel to the river bank, that is, in the direction of ice motion. It is significant that the natural configuration of these ice-attacked shores is a smooth-topped "pavement"; it was concluded that loose boulders become pressed into the mudbank to form the pavement. It was noted, however, that although the boulder pavement as a whole was stable, individual boulders were occasionally removed from the pavement and replaced by a travelling boulder from an upstream source. Thus, it seems that a smooth pavement of armor units of sufficient size could be the preferred natural condition under the impacts of ice against a slope.

The stability of armor units in coastal ice environments is not well documented, although it is known that ice push has moved boulders and trees along natural coastlines and that ice rideup on a breakwater in Denmark caused "considerable damage" to the armor layer (Brunn and Johannesson 1971 - Volume 2, Appendix 2). Danys (1978 - Volume 2, Page 75) reported that the loose rubble armor on the artificial islands in Lac St. Pierre along the St. Lawrence River were subject to combined forces of ice pileup, wave attack, and settlement action. The islands required extensive maintenance and were completely rebuilt eleven years after original construction. The armor rock used is estimated from published drawings to be about 1 to 2 tons. Other experience, however, of breakwaters located in the Gulf of Saint Lawrence shows that wave spray tends to freeze armor units in place, in effect forming a protective ice foot which forms before the presence of large ice floes and remains until after breakup (Ploeg 1980 - Volume 2, Appendix 2). A tetrapod breakwater in northern Finland also experienced the protective ice coating. Reliance on this effect is not reasonable for some locations such as the Beaufort Sea since impact by large ice floes can occur when air temperatures are above freezing.

"Bulldozing" of armor units by ice is not restricted to the water level. Moving ice sheets often contain ice ridges with keels which scour the sea bottom as they move. Kovacs and Mellor (1974 - Volume 2, Appendix 2) show side scan sonar survey records of the bottom of the Beaufort Sea which are covered with scour furrows dug by ridge keels traversing the area. Kovacs and Sodhi (1981 - Volume 2, Appendix 2) report firmly grounded ridges even at the steep-sided Fairway Rock in the Bering Strait. Scour at the toe of an armored slope by ridge keels could cause the slumping downslope of the armor layer by wave attack during the following summer season. Although a rubble mound structure is "flexible" in that dislodged units are often compensated for by the shifting of nearby units to fill the gap, damage to the supporting toe structure may lead to the collapse of large sections of the armor layer above it. Concerns of scour by ridge keels also applies to arctic submarine pipelines (Pilkington and Marcellus 1981 - Volume 2, Appendix 2).

In areas where the tides are high and the current action is strong, rubble mound structures are subject to impacts by ice floes and to "plucking" by ice action. Plucking occurs when armor becomes frozen to a piece of ice which is subsequently lifted by a high tide or a storm surge. The armor unit is "plucked" out of the rubble mound slope, floats away with the ice, and is dropped elsewhere when the bond is broken. High currents in rivers or tidal areas may cause ice impact damage. Ice floes carried by the current, and also influenced by the waves, may batter a rubble mound revetment causing displacements of armor units. Several bridge crossings and railroad revetment slopes in Cooke Inlet suffer from such ice actions; some of the armor units can be seen deposited on the mudflats at low tide.

Design Development Approach

From the foregoing review of ice-structure interaction, arctic marine rubble mound design can be divided into two main concerns:

1. Geometry of the structure (to induce ice pileup, to prevent rideup, or to permit rideup with safety),

2. Armoring of the structure (to maintain the geometry against ice and wave attack).

Since it is not clear from available information how these two parameters should be treated in the design of arctic slope protection, a "design development" approach was used in Tetra Tech's AOGA Project #126 to determine the relative effectiveness of various combinations of geometry and armor in providing good designs for a range of uses.

Geometry Considerations

The review of the available literature on ice-structure interaction, combined with knowledge of ice pileup/rideup processes and wave-structure interaction processes leads to a full range of candidate geometries. These alternative geometries progress from simple slopes to vertical walls with combinations of large-scale roughness included. The main concern with geometry features is to find the appropriate design for the degree of ice management required for the structure's function and site.

Geometry Alternatives

1. Simple Slope (various steepnesses)

2. Simple Slope with "Tank Trap" Parapets

3. Bench (or "Berm" Design)

4. Bench with "Tank Top" Parapets

5. Simple Slope with Vertical Wall at Crest of Structure

6. Simple Slope with Vertical Wall at Crest of Structure and "Tank Trap" Parapets

7. Vertical Wall at the Waterline (Caisson Design)

It must also be kept in mind in selecting a geometry that all the factors in Tables 7.2 and 7.3 apply in deciding overall if the structure is functional and economically justified. For some geometries, wave and ice behaviour may run counter to each other. For example, on flat simple slopes, wave runup is reduced, necessary armor weights are generally less, but ice rideup is more possible, and, if the slope is smooth, possibly even enhanced. For other geometries, wave and ice behaviour may both be improved. On the bench design for example, wave runup is reduced and the slope breaks may also cause ice pileup to occur. Alternatively, on vertical caisson-type designs, ice pileup is definitely initiated at the cost of high ice pressures, and fill requirements for a specific structure size are reduced at the cost of higher costs for steel or concrete for the caissons.

Armoring Considerations

The often conflicting requirements of wave and ice concerns are also manifested in the choice of slope protection armor. Again a full range of alternatives are available, some of which are appropriate to only certain of the geometry alternatives. The main objective of the armoring is to effectively maintain the slope geometry so that the ice management features designed into the structure continue to work:

Armoring Alternatives

1. Discrete Armor Units

    - Quarrystone
    - Concrete Block
    - Cast Shapes (Tetrapods, etc.)

2. Fabric Containers

    - Sand Bags
    - "Bolsacreto", "Bolsaroca"
    - Longard Tubes

3. Block and Cable Mats (various manufacturers have somewhat different products)

4. Binders

    - Soil Cement
    - Bitumen
    - Polyurethane

5. Gabions (various material types and shapes)

6. Vertical Walls

    - Sheet Pile
    - Concrete
    - Built-up walls of various other armor types above (appropriate to crest walls only)

All the factors in Tables 7.2 and 7.3 must be brought to bear on the selection decision of armor type for each individual structure being considered. In armoring considerations the requirements to armor against waves and against ice may not necessarily agree. For example, slope roughness and porosity are conventional ways to dissipate wave forces on a rubble mound structure. However, in ice, it seems that slope roughness might be appropriate to trigger ice pileup, but it might also lead to armor displacements until a "smooth" surface is presented to the ice. It is possible that armor displacement by ice in winter can be severe enough so that summer wave action will cause further damage.

Design Selections

Given the multiple choices of geometry types and armor types, the general lack of specific knowledge on ice-structure interaction, and the often conflicting requirements of wave protection and ice protection, how is the choice made of what design to implement? As in most such instances, when an optimum is sought from among several alternatives seeking to satisfy several design conditions, a rating system is necessary. The following criteria may be used to evaluate alternative designs:

Reliability/Functional Protection Provided

1. Ice management concerns: pileup/rideup/overtopping

2. Sensitivity of structure to damage

Construction Costs

3. Constructability of the design for the site and in arctic conditions

4. Availability of required materials

5. Tradeoffs of material types

Maintenance Costs

6. Durability under wave action

7. Durability under ice action

The relative weights for the seven criteria are entirely case by case dependent. For example, a permanent structure with an intended long service life in severe wave and ice conditions will require higher weighting factors for reliability and functional protection and lower weighting factors on, perhaps, construction costs. For temporary structures in more sheltered areas, perhaps reduced constructed costs would be considered relatively much more important.

In AOGA Project #126, such a rating scheme was used to examine all the various combinations of geometry and armor alternatives in order to eliminate from consideration those least applicable to the questions at hand. Then, several of the more highly rated alternatives were designed and evaluated under wave and ice attack by model studies. Tetra Tech directed and managed the program and conducted the wave model investigations. Arctec, Inc. conducted the ice model investigations, and Austin Kovacs consulted on matters of ice-shore interaction, prototype ice conditions, and model data interpretation.

Temporary Slope Protection

Arctic experience has proven that 2 to 4 cubic yard sandbags with an underlying filter cloth system are an economical choice for temporary slope protection. Advantages of the sandbag slope protection system are:

- Proven by prior arctic construction experience,
- Maximum use of locally available material (i.e. sand and gravel),
- Rapid mobilization and short construction time,
- Suitability for expansion or removal, and
- Relatively low cost.

Disadvantages of the sandbag slope protection system are:

- Expected high maintenance,
- Limited durability, and
- Vulnerability during construction.

Stability Calculations

The lateral ice forces on a causeway or breakwater structure may be estimated from a method suggested by V. Vivatrat and J.R. Kreider ("Ice Force Prediction Using a Limited Driving Force Approach", OTC 4115, Proceedings of the Offshore Technology Conference, Houston, Texas, 1981). Once this ice force per linear metre or linear foot of the causeway is computed, the stability of the structure may be checked for various truncation type failures as shown in Figure 7.18. Truncation type failures are discussed in a later section.

7.5.2.2 Piled Structures

The acceptable location for a pile type structure would be a well protected location where deep water occurs near the shore and where lateral ice loads from floating ice sheets are small. There should be limited wind fetches, protection by capes and unilateral currents parallel to the shore. In this type of location, a considerable quantity of ice may flow past the dock, but very little of it should impinge directly against it.

An example of a dock for such a location is reported by H.R. Peyton in "Ice and Marine Structures", Ocean Industry, March, September and December, 1968 on a dock under construction in Anchorage, Alaska.

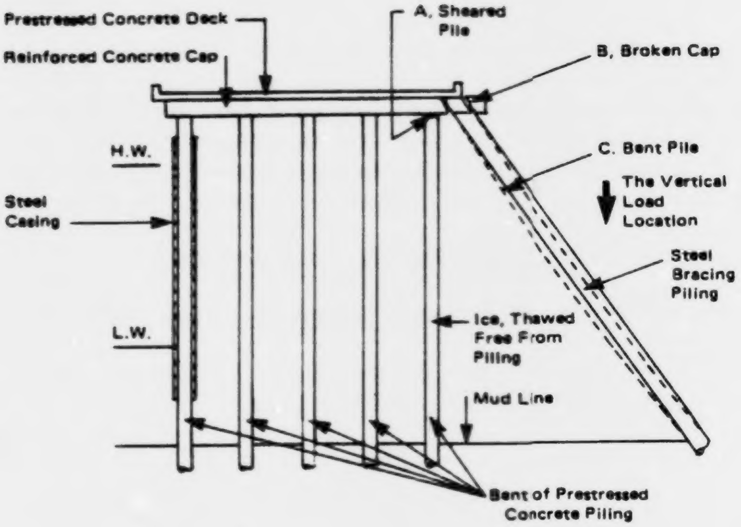

Prestressed Concrete Deck
Reinforced Concrete Cap
A, Sheared Pile
B, Broken Cap
H.W.
C. Bent Pile
The Vertical Load Location
Steel Casing
Steel Bracing Piling
L.W.
Ice, Thawed Free From Piling
Mud Line
Bent of Prestressed Concrete Piling

Figure 7.1 Schematic diagram of large vertical loads imposed on a piling bent with diagonal bracing. The failure occured when ice mass thawed free from piling during low tide.

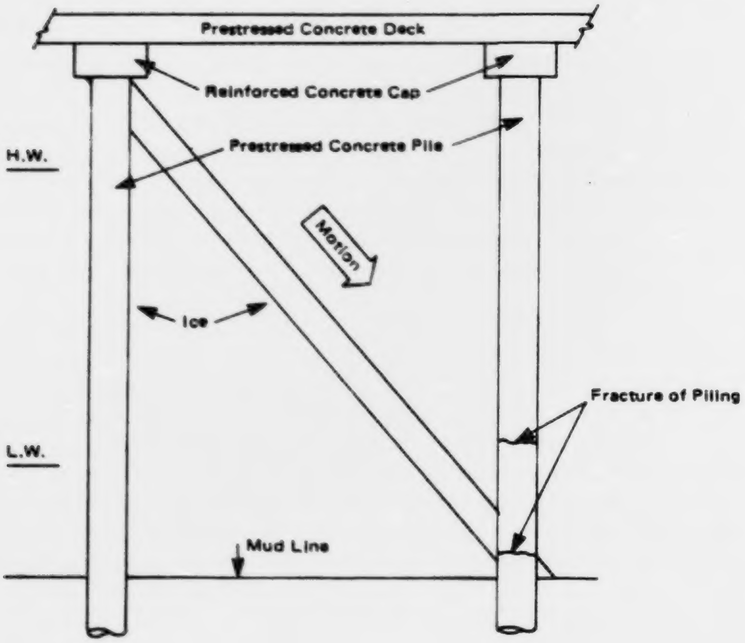

Prestressed Concrete Deck
Reinforced Concrete Cap
H.W.
Prestressed Concrete Pile
Motion
Ice
Fracture of Piling
L.W.
Mud Line

Figure 7.2 Schematic of a second type failure. Ice on diagonal brace acted as a bead on a string, slipping down member with sufficient velocity to exert tremendous force as shown.

The partially build dock failed due to ice loads.

The design incorporated closely spaced vertical and batter steel piles with diagonal bracing to resist longitudinal and lateral horizontal forces (this type of structure was found to be economically attractive due to suitable soil conditions). The spacing of the piles was such that separate ice masses formed above the vertical and batter piles.

Due to this configuration, two general types of failure occurred during the spring when the ice masses thawed. The first type of failure is shown in Figure 7.1 in which the entire weight of the ice mass at low tide was supported by the batter pile. Three specific types of structural failures occurred and are shown at locations A, B and C. Raking of the ice mass broke the concrete piling free of the relatively light cap at A, both elastic and permanent bending occurred in the batter pile at C and the cap was badly fractured at B due to joint rotation between the batter pile and the cap. The second general type of structural failure is schematically shown in Figure 7.2 where the ice which had formed on a single longitudinal bracing pile acted like a bead on a string. It is surmised that friction held the bead of ice at high tide until the time of low tide (tidal range of 30 feet), when the ice bead of several tons weight slid down the diagonal bracing and fractured the vertical concrete piling in the adjacent bent.

From these failures, it is evident that the design of piled structure in ice conditions should be simplified and the use of batter piles and diagonal bracings in the tidal zone avoided. Use only vertical piles as far as possible.

Ice Forces Against Vertical Piles

The predominant lateral ice forces are generated by large ice floes being forced past the piled structure by wind and tidal currents. The maximum loads on the vertical piles are generally induced when the ice sheet fails by crushing against the pile, with a clean slot being cut which is about the diameter of the pile (Figure 7.3).

The magnitude of this lateral ice load can be computed from indentation theory using the Afanas'ev curve for the indentation coefficient k (Figure 7.4).

$q = m \sigma_c k$ -- (1)

where:

q = specific or effective ice pressure on the vertical pile

m = shape coefficient (1.0 for flat surface and 0.9 for semicircular face)

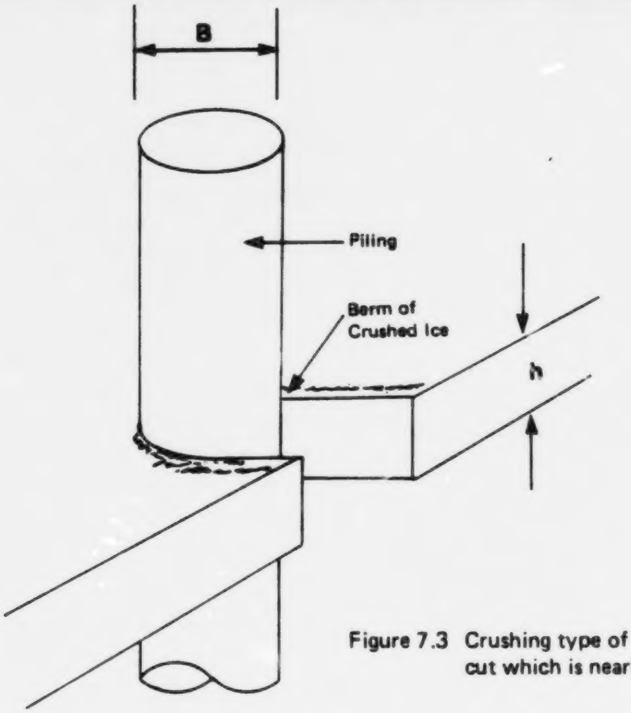
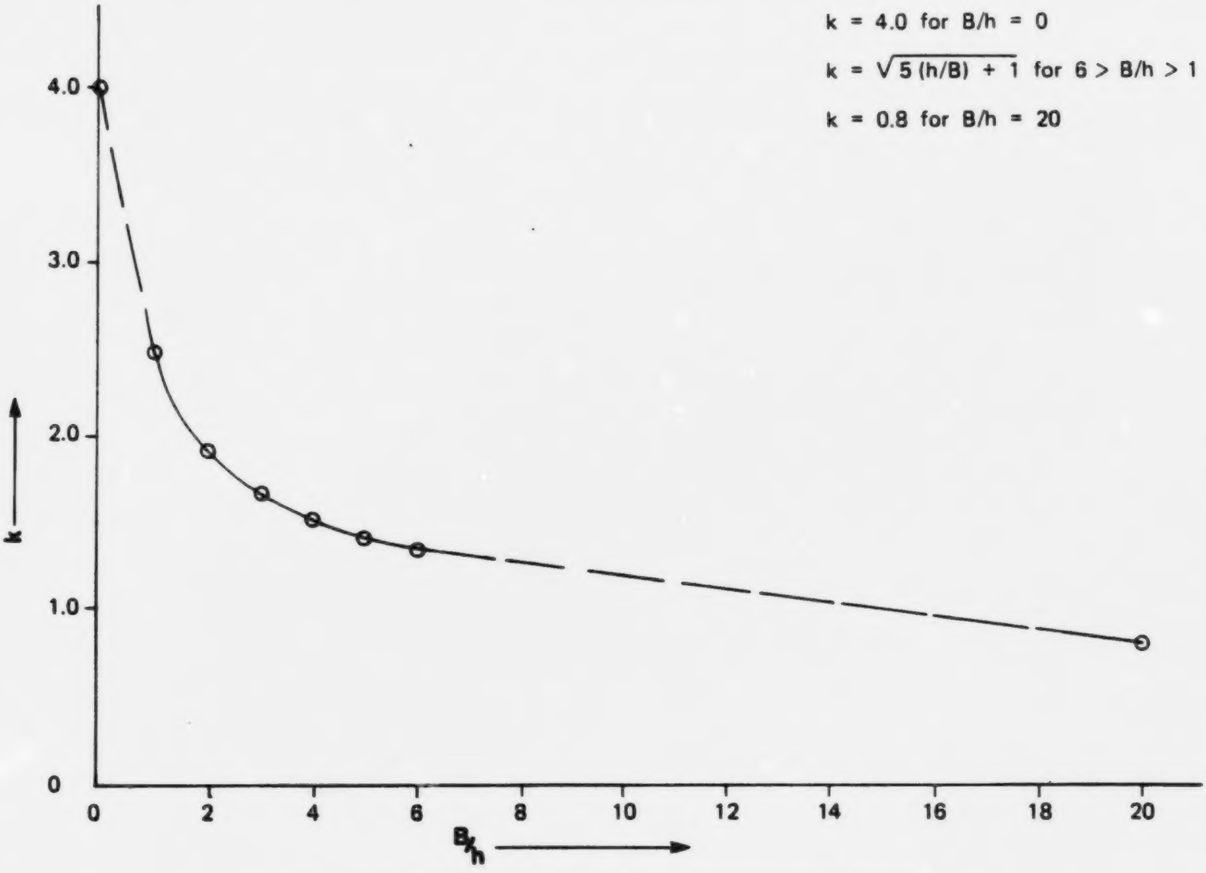

B
Piling
Berm of Crushed Ice
h

Figure 7.3 Crushing type of ice failure with a clean slot being cut which is nearly the diameter of the pile.



$k = 4.0$ for $B/h = 0$

$k = \sqrt{5\,(h/B) + 1}$ for $6 > B/h > 1$

$k = 0.8$ for $B/h = 20$

Figure 7.4 Afanas'ev Curve for the Indentation Coefficient k

σ_c = uniaxial compression strength of ice (cube strength)

k = indentation coefficient from Figure 7.4, where aspect ratio =

$\frac{B}{h} = \frac{\text{width of structure}}{\text{thickness of ice}}$

The total or global force on the structure $P = q \cdot Bh$

Ice Thickness

The thickness of the ice sheet should be obtained from local records if available and where they are not available, may be estimated from the following equation:

$h = kA\sqrt{S}$ -------------------------------------- (2)

where:

h = estimated ice sheet thickness, inches

k = ice growth constant (values from 0.5 to 0.9; the lower value reflects snow cover and flowing water, while the higher value suggests wind blown surface over still water)

A = ablation constant (ice decay during breakup, values from 0.8 to 1.0; lower value for south flowing rivers and higher value for ice movement occurring at any season)

S = freezing index in °F - days

Ice Strength

Traditionally, Canadian practice has used the nominal values of effective pressure q, without making a clear distinction between ice strength and pressure. For example, the pre-1974 Canadian Standards Association (CSA) highway bridge code S-6, following the corresponding code of the American Association of State Highway Officials (AASHO), simply specified an effective pressure of 400 psi (2800 kPa) for all circumstances. The 1974 CSA Code allows for a range of effective pressure q from 100 psi to 400 psi (700 to 2800 kPa) depending on the expected physical characteristics of the ice.

While it is true that most structures so far installed in ice affected areas have been designed to Canadian, U.S. and USSR codes which call for effective ice pressures no greater than 400 psi (2800 kPa) and these structures as far as known have performed adequately, the problem facing the arctic offshore engineer is that in-situ indentation tests carried out on arctic ice have indicated the possibility of considerably higher effective pres-

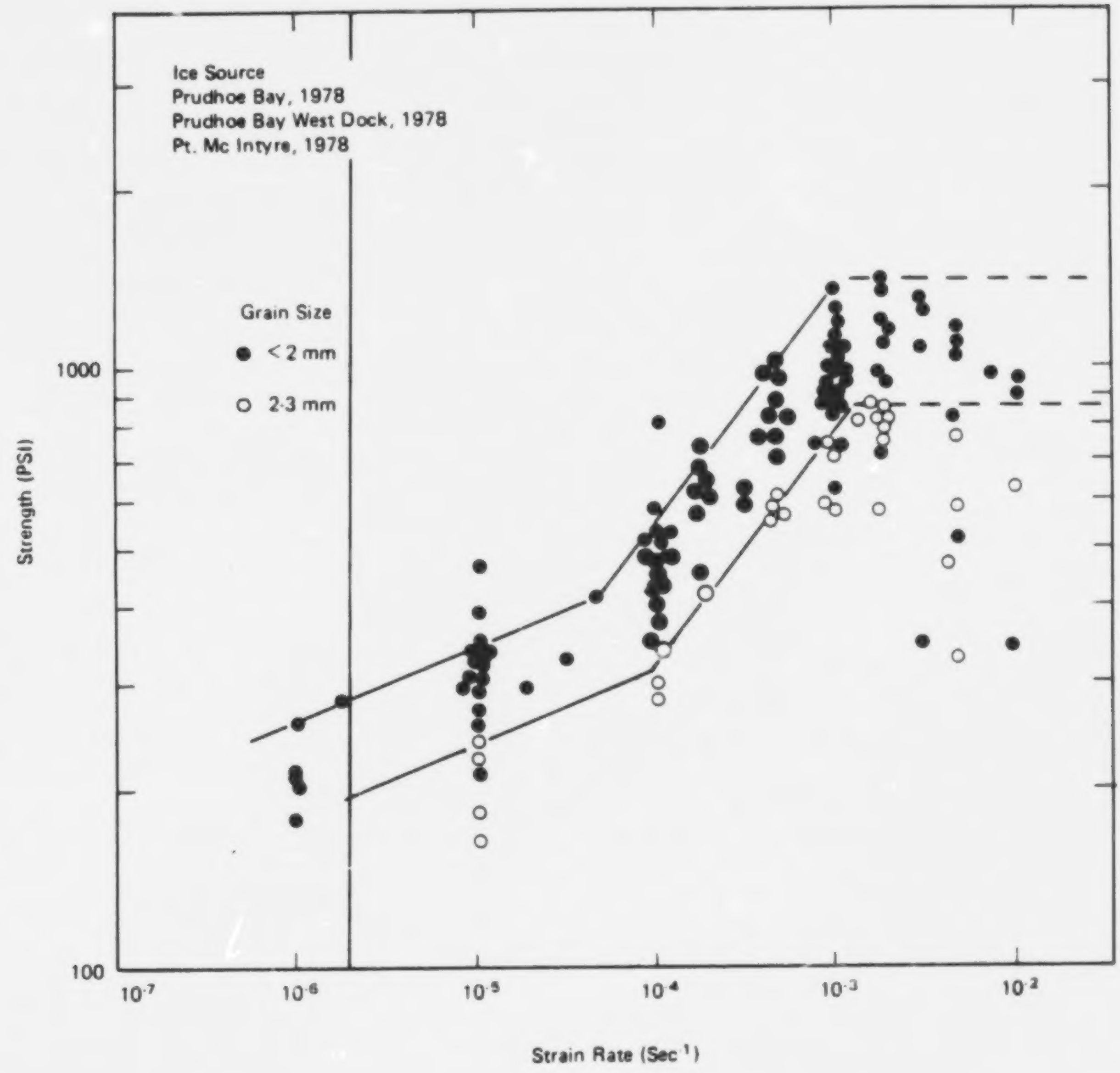


Figure 7.5 Compressive strength of granular sea ice as a function of strain rate (Exxon 1979)

sures, perhaps as high as 1000 psi (7000 kPa). For this reason, the value of 400 psi (2800 kPa) effective pressure should not be regarded as the upper limit for the design of arctic structures. The value of ice strength chosen for design will depend primarily on salinity, age and type of ice, temperature and ablation.

Rate of Loading

The effective ice pressure is also affected by the rate of loading. Because of the visco-elastic nature of ice, the effective ice strength is low for very low rates of strain or loading. With increasing strain rates, the ice strength increases, but only up to a certain peak or plateau, after which the ice strength will no longer increase with strain rate. According to the Exxon tests (1979), this maximum peak strength is attained at a strain rate of about 10^{-3} per second (Figure 7.5).

Force Oscillations

The lateral ice load due to crushing of the ice sheet on the vertical pile is not a constantly applied force, but rather a series of triangular load pulses (Figure 7.6). This dynamic load oscillates between zero and the peak value with a frequency of oscillation of roughly 1 second, as measured by Peyton in Cooke's Inlet.

Relatively light structures installed in ice environments have been observed to exhibit severe vibrations, sometimes referred to as "ratcheting". The dynamic interaction between sheet ice and flexible indenters was recently reviewed by Määttänen who developed a procedure for predicting the dynamic loading from moving ice sheets. Ice structure interaction is also discussed by Croteau (1983 - Volume 2, Page 73).

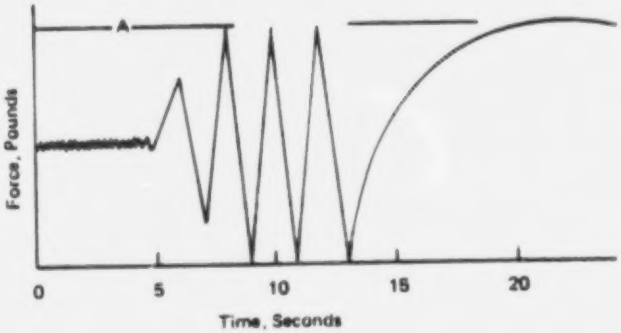


Figure 7.6 Oscillating force on the structure is implied to be similar to this sketch. Most probably there is some structure response aspect to the system; however, this type of failure and frequency of oscillation is primarily an ice property.

The design of leg structures must allow for significantly higher local pressures than those indicated by the average pressure determined from the indentation equation. This is to account for the brittle behaviour of ice which results in non-simultaneous fractures observed to occur across indenters. It is suggested that the local contact pressure curve proposed by Bruen et al. (1982 - Volume 2, Page 254) be used for selecting a design pressure for first year ice conditions.

Dynamic Amplification

The dynamic amplification due to the triangular load pulse can be estimated from Newmark's graph in Figure 7.7 which indicates a maximum amplification factor of 1.5 at reasonant frequencies ($\frac{\tau}{T} = 1.0$) where $\frac{\tau}{T}$ is the frequency ratio =

$$\frac{\text{period of triangular load pulse}}{\text{natural period of structure}}$$

Fatigue

The force time diagram in Figure 7.7 may also be used to construct a load spectrum for the structure in order to assess its fatigue life. The load spectrum will indicate the cumulative damage to the structure over its useful life by using a modified Miner's Rule. Where load spectrum information is not available, the simpler S-N method as indicated in CSA-S16 may be used instead.

Pressure Ridges

Where the piled structure is subject to pressure ridge loading, the ice forces will be considerably higher than that due to the ice sheet alone. Force measurements by K.A. Blenkarn ("Measurement and Analysis of Ice Forces on Cooke Inlet Structures", Offshore Technology Conference, Houston, Texas, 1970) indicate that first year ridge loads range from 1.5 to 3.6 times the load from the parent sheet alone. Based on this information, a ridge factor of 2.0 is sometimes used to account for pressure ridge loading. This is rather empirical. A more reliable method is to compute the "Upper Bound of Ridge Pressure on Structures" as recommended by A. Prodanovic (POAC 1981 - Volume 2, Page 291) using an idealized and simplified ridge profile proposed by Kovacs (APOA Project #89, 1975.

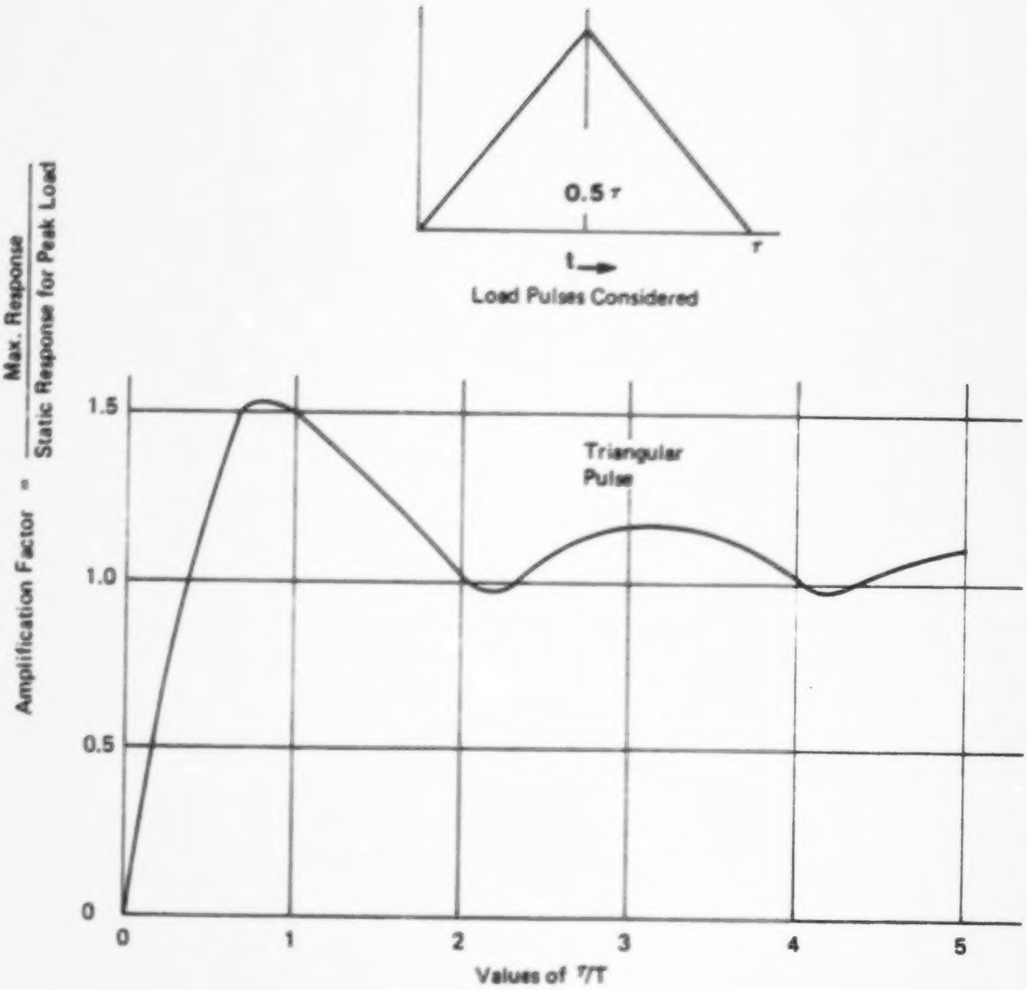


Figure 7.7 Response Spectra

Alternately, a probabilistic approach may be used to assess the risk/safety of the structure if sufficient data on the sizes and geometry of pressure ridges are available for the area.

Uplift and Downdrag

When an ice sheet freezes around a pile in tidal waters, a rise in the water level will induce an uplift on the pile while a fall in the water level will induce a downdrag. The magnitude of these uplift or downdrag forces may be obtained by treating the ice sheet as a semi-infinite plate, supported on an elastic foundation (provided by the sea-water) and loaded at the pile locations by using the graphical solutions provided by D.E. Nevel ("A Semi-Infinite Plate on an Elastic Foundation", CRREL Report #136, 1965 - Volume 2, Appendix 2) or by G.G. Meyerhof ("Bearing Capacity of Floating Ice Sheets", Trans. ASCE, 127, 1962 - Volume 2, Appendix 2). The upper limit of this uplift or downdrag force is of course the ice adhesion strength, which varies inversely with the diameter of the pile and other parameters, multiplied by the contact area around the pile.

7.5.2.3 Gravity Structures

These structures take the form of steel sheet pile cells, or reinforced concrete cribs usually filled with a granular material or rock fill. In some sites rock filled timber cribs can be used. Gravity structures may be cone shaped, such as typical lighthouse structures in Canada, or as adapted for some arctic artificial island structures.

Large Cylindrical Structures

Large steel sheet pile cells or reinforced concrete cells or artificial islands are in this category.

The average effective ice pressure is considerably less in case of a large cylindrical structure as compared to a small one, such as a pile. Apart from the aspect ratio, there is the consideration of the probability of non-simultaneous failures at the contact surface. The problem of ice forces on wide structures is addressed in a paper, "A Statistical Prediction of Effective Ice Crushing Stresses on Wide Structures" by P.R. Kry at the Symposium on Ice Problems, IAHR, Lulea, Sweden in 1978 (Volume 2, Page 106). A statistical theory is presented to entrapolate observed effective ice pressures on narrow structures to those on wide structures. To this end, the contact width is subdivided into identical but independent zones or channels wherein the stresses are not influenced by adjacent zones or channels. The average stress in each zone is presumed to be described by the empirical load distribution for a narrow indentor. Because of supposedly variable local contact conditions in the various zones at any time, their

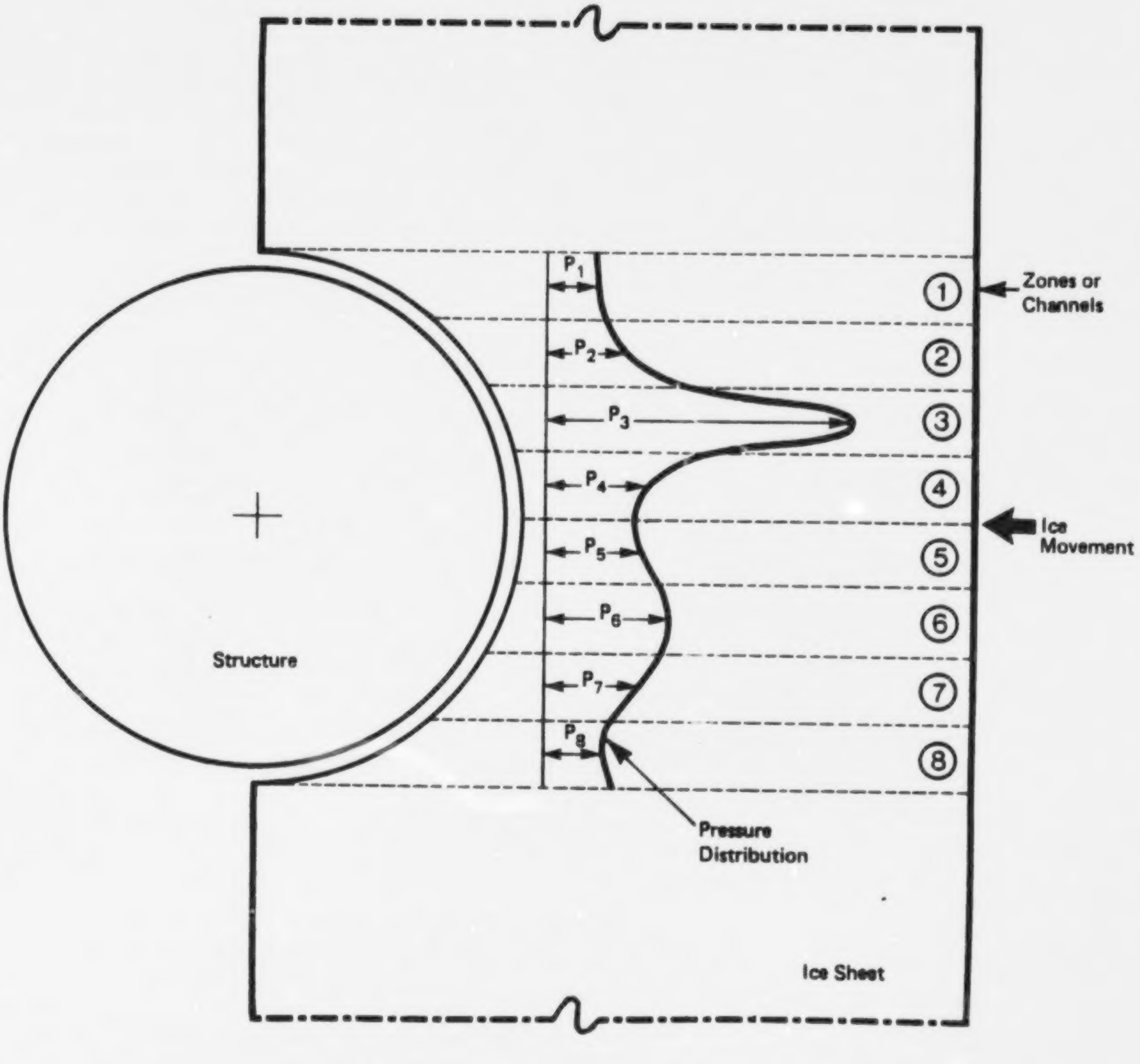

P1
P2
P3
P4
P5
P6
P7
P8
①
②
③
④
⑤
⑥
⑦
⑧
Zones or Channels
Ice Movement
Structure
Pressure Distribution
Ice Sheet

Figure 7.8 Interaction of ice sheet with wide structure

stress levels are different and the probability distributions defining the loads are statistically independent, though identical. This concept of independent zones or channels for non-simultaneous ice failures provides a plausible explanation for the reduction of design effective stresses for wide structures.

For the molded type of contact between an ice sheet and a wide structure, the report on "Interaction Between a Wide Structure and Thick Ice Cover" by H.T. Yan and S.H. Zemell for Gulf Canada Resources (1982 - Volume 2, Appendix 2) addresses the problem of effective design ice pressures for this condition. As in a paper by Kry, the contact width is divided into identical but independent zones or channels. However, the non-simultaneous failure in the zones or channels is explained by the postulation that the molded contact face of the ice sheet is made up of "hard" and "soft" ice zones, and that the "hard" ice will fail before the "soft" ice because it attracts a greater proportion of the contact load to itself (Figure 7.8). Thus, during the initial breakdown of the molded contact face, zones of "hard" ice will experience maximal effective pressures. However, since the elastic limit for

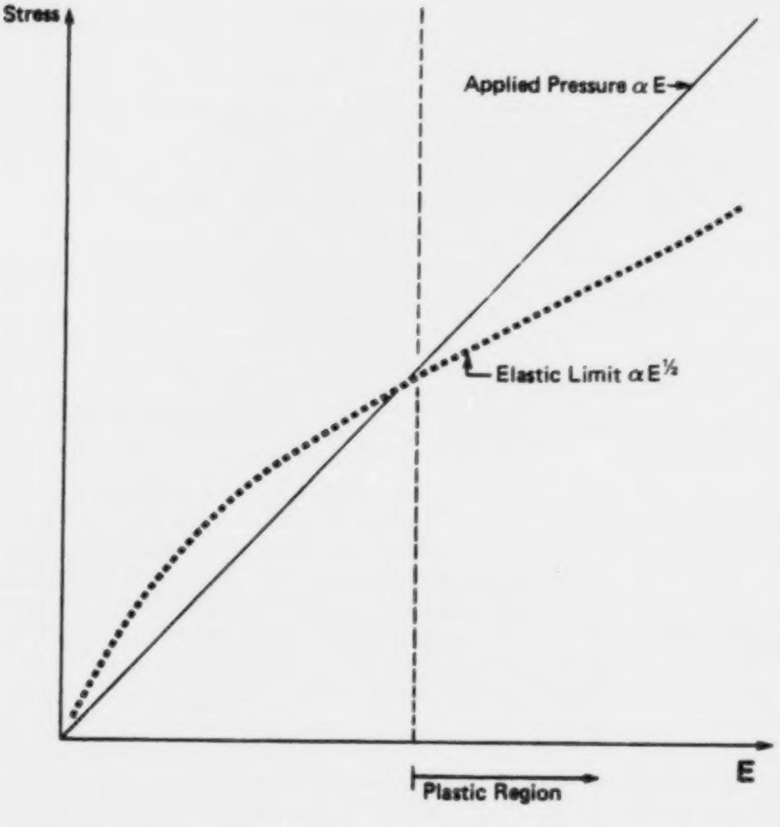


Figure 7.9 Applied pressure and elastic limit versus E

ice varies almost as the square root of E (Young's modulus for ice), whereas the effective pressure is directly proportional to E, it is evident that the harder or stiffer ice will reach its elastic limit first. In other words, the contact pressure increases at a faster rate than the increase in ice strength with E, as indicated in Figure 7.9. This will cause the "harder" and "stiffer" ice to fail first, before the "softer" ice can fail, and will create the non-simultaneous failure condition in the channels.

The design effective ice pressure is then obtained by a probabilistic approach using the Monte Carlo method and posulating ice properties as stochastic.

Local Ice Pressures

While the above approach of non-simultaneous failure zones would considerably reduce the global ice forces for wide structure, there is no corresponding reduction in the local ice pressures. If complete plasticity is assumed, the computed local ice pressures are many times the global pressures and hence are very high. Even when some brittle failure is asumed, the local ice pressures are somewhat reduced but will remain high, with a value of 1000 psi or more.

These high local ice pressures can pose severe structural problems both for steel as well as for concrete structures.

In steel structures, J.L. Coburn recommends ("A Rational Basis for Hull Ice Strengthening Criteria", STAR Symposium, Society of Naval Architects & Marine Engineers, Ottawa, Canada, 1981 - Volume 2, Appendix 2) that the use of plastic design procedures for the shell plating, taking into account "catenary" or "tension net" action based on the "large deflection theory" and accepting some permanent strains in the process of resisting the high localized ice pressures. He quotes U.S. Coast Guard experience that failures which have taken place have almost totally confined to the supporting frames and not to the shell platings themselves. Also, there is some concern that progressive collapse can be associated with high localized ice loads and this possibility should be thoroughly checked.

For concrete structures, the high local ice pressures can pose severe problems not only in bending but also in shear, particularly punching shear. The resistance thick walled concrete shell structures subject to intense local loading, has been the subject of numerous laboratory and analytical investigations. Because of the low span-to-depth ratio of the concrete shell, and the presence of high percentages of reinforcing and/or prestressing steel, the behaviour of the shell or slab is significantly better than given by conventional building codes such as ACI or CSA, which are relevant to high span-to-depth ratios and low steel percentages. The current AOGA Project 152 "Punching Shear Resistance of Concrete Shells and Slabs" (1982) is intended to provide more appropriate design rules for this condition.

This punching shear problem in concrete shells is well described by B.C. Gerwick Jr. in "Concrete Structures for the Arctic" (Proc. of 2nd Annual MIT Sea Grant College Program Lecture and Seminar, 1983 - Volume 2, Page 276).

The term "punching shear" is really improper for such a case. In reality, the initial effect is primarily flexure, with severe cracking forming opposite the load. As the reinforcing steel reaches yield, the moments are transferred to the supports. Inclined diagonal struts form within the shell. The high intensity of load on them leads to diagonal laminar cracking within the strut, just as in a column. Ultimate failure will then take place by punching shear along rather flat diagonals or, if the struts have been sufficiently confined by stirrups, by crushing at the inner face of the haunch. In some slab tests, failure has also occurred in crushing under the load.

This indicates the need for high percentages of shear steel (stirrups) and for confinement of the compression zones. Closed stirrups often fail to develop yield strength prior to laminar cracking failure: there is insufficient room to properly bond them. Use of headed stirrups or specially-fabricated stirrups, which mechanically are fixed to the inplant steel, are therefore much more efficient. If stirrups are used their lap should occur in the confined-section rather than at the face. As in column confinement, mechanical splicing or closure is most effective.

The nominal shear strengths so developed are significantly greater than those predicted by simple application of code formulae. Since the concrete, near ultimate, will have high through-wall tension, it seems advisable to rely entirely on the through-wall steel to resist the transverse tension.

Stability of Steel Sheet Pile Cells

The steel sheet pile cells should be checked for stability against lateral ice forces. The method by B. Hansen and developed by K. Ovesen ("Cellular Cofferdams, Calculation Methods and Model Tests", The Danish Goetechnical Institute, Bulletin No. 14, 1962) where the cell stability checked for base rupture and body-rotation about a pole, would be applicable to this case (Figure 7.10).

Cone Shaped Gravity Structures

The advantage of a cone shaped structure is that it tends to induce flexural failure in the ice sheet and so result in substantially lower loads on the structure, as compared to the case where the ice sheet fails by crushing. The total ice load on the cone shaped structure in this case is not only the rupture load of the ice sheet, but must include the ride up load or work which is done by broken ice pieces which ride up and around the structure. The rupture load may be computed from Nevel's graphs (CRREL Report #136, 1965 - Vol. 2 Appendix 1) but the ride up loads cannot be easily computed.

Tests by Edwards and Croasdale ("Model Experiments to Determine Ice Forces on Conical Structures", Symposium on Applied Glaciology, Cambridge, England, 1976 - Volume 2, Appendix 2) indicate that the lateral ice force on a 45° cone may be expressed as

$$H = 1.6\,\sigma t^2 + 6\,\omega D t^2 \text{ ---------------------------- } (3)$$

where:

H = lateral ice force, kN

σ = flexural ice strength, kPa

t = ice thickness, m

ω = unit weight of ice, kN/m^3

D = cone diameter, m

The first term can be considered as the force necessary to fail the ice in bending while the second term is the force necessary to push the broken ice up and around the cone. Implicit in both terms is the friction coefficient μ which was about 0.1 in these tests.

From statics, the relation between the vertical force 'V' and the lateral ice force 'H' is given by

$$\frac{H}{V} = \frac{\sin\alpha + \mu\cos\alpha}{\cos\alpha - \mu\sin\alpha} \text{ ---------------------------------- } (4)$$

where:

μ = friction coefficient

α = cone angle

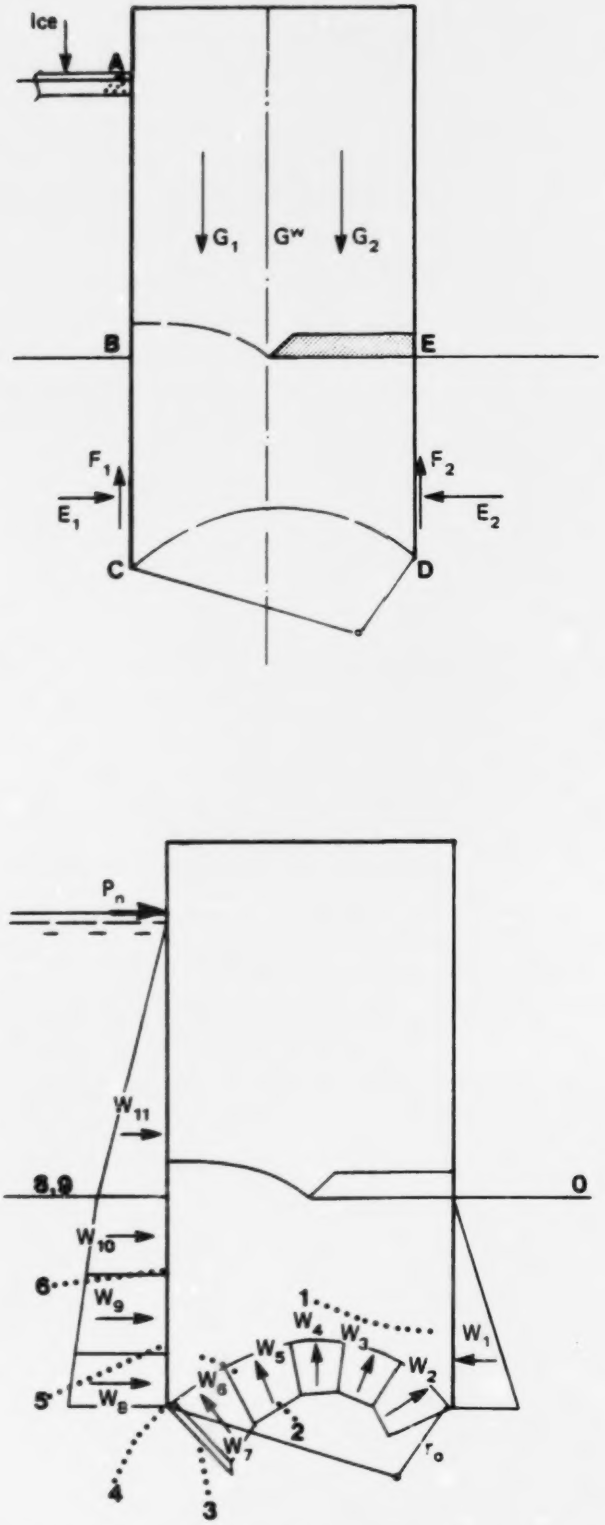

Ice
A
G₁
Gʷ
G₂
B
E
F₁
F₂
E₁
E₂
C
D
Pₙ
W₁₁
8,9
O
W₁₀
6
W₉
1
W₄
W₃
W₅
W₁
W₂
W₆
5
W₈
2
W₇
r₀
4
3

Figure 7.10 Stability Analysis: Forces on Moving Body of Earth

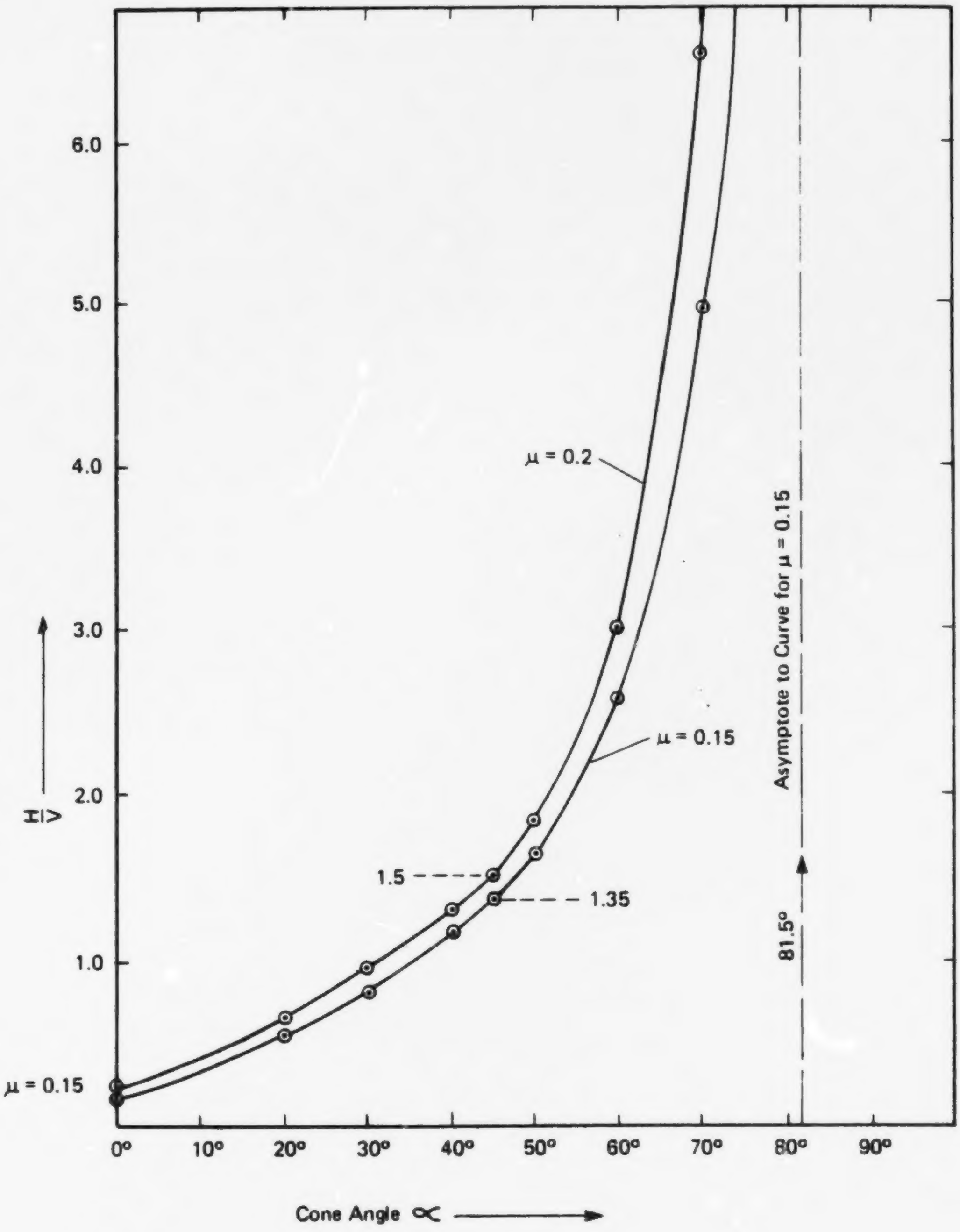
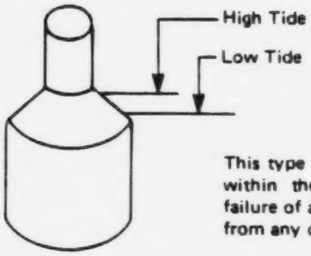
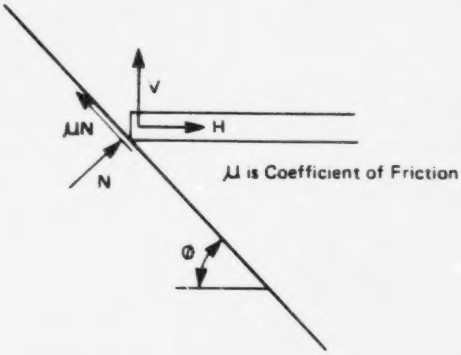


Figure 7.11 Graph of $\frac{H}{V}$ for $\mu = 0.15$ & 0.20 for Various Values of Cone Angle


High Tide
Low Tide

This type of conical section could be used within the tidal range to force bending failure of an ice sheet which can hit the leg from any direction.


V
H
μN
N
μ is Coefficient of Friction
Ø

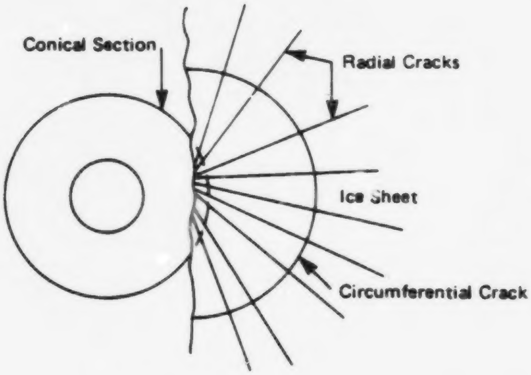
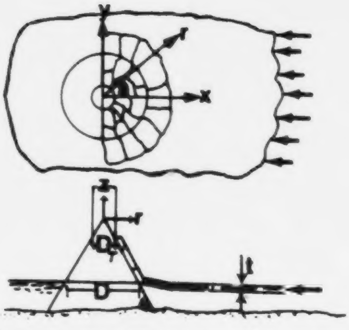

Conical Section
Radial Cracks
Ice Sheet
Circumferential Crack

Figure 7.12 Plan view of an ice sheet being failed. First the radial cracks form and then the sheet fails totally with the formation of the circumferential crack.



Ice Sheet Failure Against a Conical Structure (After Ralston, 1979)

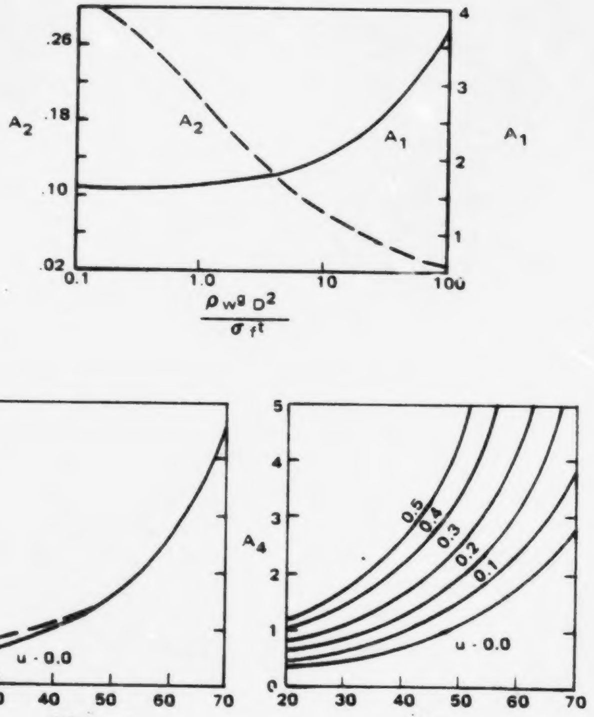


Figure 7.13 Dimensionless Coefficients (A_1, A_2, A_3 and A_4) for Plastic Analysis (After Ralston, 1979)

The relationship between H and V for various values of μ is plotted on the graph in Figure 7.11 and diagramatically illustrated in Figure 7.12.

For cone angle $\alpha = 45°$,

$$\frac{H}{V} = \frac{1 + \mu}{1 - \mu} \text{ --- } (5)$$

A general solution of ice cone interaction has been obtained by T.D. Ralston ("Plastic Limit Analysis of Sheet Ice Loads on Conical Structures" - Volume 2, Appendix 2). The horizontal and vertical forces exerted by ice failing in bending can be determined from the following equations:

$$H = \left[A_1 \sigma t^2 + A_2 \omega t D^2 + A_3 \omega t_R (D^2 - D_T^2)\right] A_4 \text{ -------- } (6)$$

$$V = B_1 H + B_2 \omega t_R (D^2 - D_T^2) \text{ ---------------------------- } (7)$$

where:

H = horizontal force on the cone, kN

V = vertical force on the cone, kN

ω = unit weight of water, kN/m^3

μ = ice structure friction coefficient

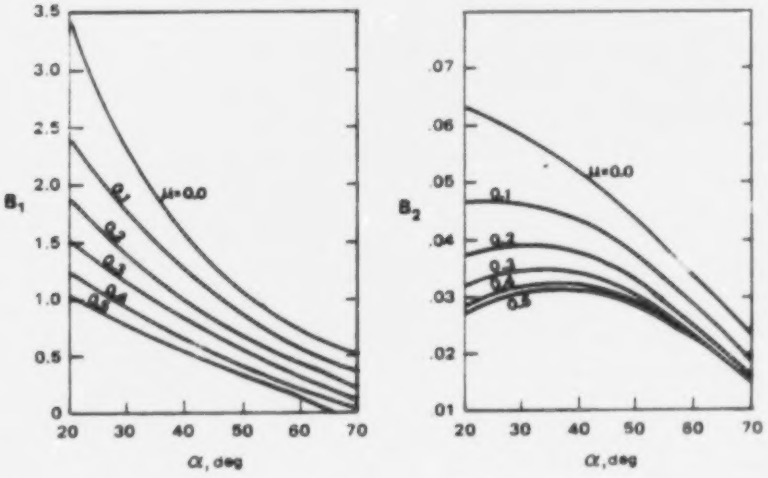


Figure 7.14 Dimensionless Coefficients (B_1 and B_2) for Plastic Analysis (After Ralston, 1979)

σ = sheet ice bending strength, kN/m^2

t = ice sheet thickness, m

t_R = ice ride-up thickness, m

D = waterline diameter of cone, m

D_T = top diameter of cone, m

α = cone angle, as measured from horizontal

A_1, A_2, A_3, A_4 & B_1, B_2 = dimensionless coefficients from graphs (Figures 7.13 and 7.14)

The above equations may not be appropriate for wide structures or very steep cone angles. In this case, the forces exerted on the structure must be analyzed with elastic theory and corrective factors obtained from model studies.

Adfreeze

The sea ice is not necessarily in continuous motion. It is therefore possible for broken ice features and the surrounding ice sheet to become frozen to the cone shaped structure during a quiet period. This phenomenon is called adfreeze and can defeat the purpose of using a cone shaped structure to induce flexural failure in the ice sheet. The adfreeze bond must be broken before other failure modes can be induced. Adfreeze can be avoided by heating of the cone shaped structure or by the use of special coating developed for this purpose. (G.H. Johnston, 1981; pp. 226-267 - Vol. 2, Page 196).

Caisson Retained Island Gravity Structures

Three levels of ice loading on a confined berm or mound should be considered for design purposes. The first level is the global ice force which will govern foundation design. The second level is the distribution of this global design force as well as smaller design forces in the structure, with a view to determining ice induced forces in primary structural components. The third level is the local design ice pressures used to size the structure components which form the first line of resistance to ice features.

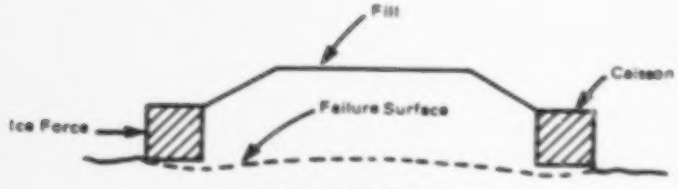
Confined berms are expected to be used primarily in shallow water areas dominated by first-year ice features. There is a small but finite possibility that multi-year ice features will be encountered and wide indenters should be capable of resisting reasonable levels of multi-year ice loading, such as can occur as a result of summer ice pack invasions. The dominant feature of this loading regime is likely to be rafted first-year ice or rubble fields with consolidated thickness of 3.7 to 4.6 m in the Southern Beaufort Sea.

The global loads applied to wide indenters can be computed using the principles outlined by Exxon (1979) for application to artificial islands. The approach uses indentation theory with strain rates selected from design ice velocities for the installation loction. This approach is in a fairly plastic fashion. Application of the methodology requires consideration of situations ranging from the breakout of an island frozen into a relatively intact large floe to continuous crushing. Breakout is conceptually the worst condition since the ice is fully adfrozen and the contact factor is presumably 1.0. However, the strain rate associated with breakout is less than the strain rate associated with steady indentation.

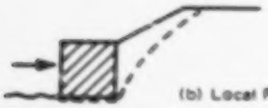
The behaviour around many grounded multi-year ice features and ice islands shows that failure will usually take place in the first-year ice as transmitting agent impacting on the multi-year grounded feature rather than within the contact mass, multi-year feature itself. In such cases, the force applied by the blocked multi-year feature to the structure will be governed by the ability of the first-year ice to apply this force. Vivatrat and Kreider (1981 - Vol. 2, Appendix 2) have estimated that this force is in the order of 40 to 50 kips per ft., being typically the force involved with ridge building processes against grounded features. As has also been observed in practice, ridge building does not occur simultaneously over the entire length of the ridge. It is a function of the initial shape of the colliding ice features.

Caisson retained island structures require a number of foundation stability analyses which differ from those for a conventional monolithic gravity platform. The global stability of the whole island must be considered as in the truncation mode of failure near the toe level of the caissons shown in Figure 7.15. In addition, local failure problems such as the passive failure of backfill behind the caisson must be considered as indicated in Figure 7.16. For the two-dimensional problems shown, certain designs result in a tendency for the caisson to ride up relative to the soil, inducing a negative skin friction condition in the backfill. This results in a passive pressure coefficient substantially less than the zero friction case. The potential for this type of failure should be examined, taking into account the overall behaviour of the caisson unit, as well as its interaction with other units.

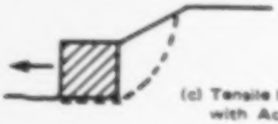
There is a tendency to focus on compressive loadings since these are much higher than the tensile forces from ice. However, the problem of breakout from an adfrozen ice sheet must also be considered as shown in Figure 7.15. In this event, the force from the backfill and the tension applied by the ice sheet combine to force the caisson outward.



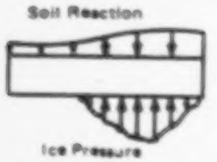
(a) Global Truncation



(b) Local Passive Failure



(c) Tensile Ice Breakout Load with Active Soil Pressure



(d) Rotational Instability in Plan

Figure 7.15 Instability Modes to be Considered in Caisson Design

Figure 7.15 shows one of the more critical loading cases for a typical caisson unit. The ice load generally is not applied symmetrically on the caisson unit, so that a two dimensional analysis of the kind shown in the Figure is not usually the governing condition. Rather, it is necessary to consider eccentricity of the ice force in plan. This results in a tendency toward rotational instability of the caisson unit. The caisson units themselves must be designed to resist the applied ice loads. Global analyses must be performed which allow for variations both in the ice load distributions and in the support from the soil. A preferred approach is to set up a finite element model of the caisson unit and to simulate the soil reactions as a set of Winkler type springs. Modeling is complicated by the fact that the soil can be either a load or a reaction depending on the deformation of the caisson. Further complications are introduced occasionally by a tendency for gapping to develop between the caisson unit and the soil. This generally requires an interative analysis procedure with modifications to the soil springs and loading conditions.

The problems of soil-structure interaction and the effects of this on structural loads in primary caisson components become more important as the caisson gets larger and are most important in the case of monolithic ring systems such as the MAC caisson. Careful judgement is required in selecting and utilizing the soil-structure interaction analysis models. Selecting the loading scenarios to go with these models is also important. In the case of multiyear ice impacts, the ice force prediction model can be used to develop the loading case. However, it is not only the multiyear ice situations which require some localization of the ice load. Even in a first-year ice environment, the observation of non-simultaneous failures across indenters requires the designer to simulate this condition. For example, if the global load has been computed using a contact factor of say 0.3, this may be thought of conceptually as the global load being applied over not more than about 0.3 of the equivalent structure diameter at a given instant.

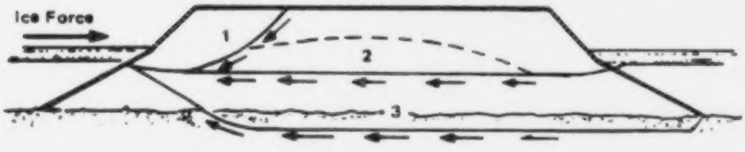
Loads associated with ice diversion and the buildup of features such as rubble piles must also be considered. Rubble piles form by the piling up of ice blocks, and an allowance should be made for the forces from large ice slabs being pushed up and over the top of a rubble pile.

Unconfined Berms and Mounds

Soil Strength and Resistance:

The mass and strength of a fill island is used to resist ice forces through gravitational forces. The strength of the unfrozen fill depends on the grain shape and soil structure. The strength of the frozen fill depends on the frozen and unfrozen moisture and the degree of salinity of the moisture within the fill voids, the number and size of ice lenses contained in the fill, the temperature of the frozen soil, and on the duration of loading.

The lateral ice loads on a fill island must be resisted by the soil strength or shearing resistance of the soil along several possible failure planes. Potential failure planes exist at the edge through the seabed (shown in Figure 7.18). The shearing resistance is equal to the weight of the fill above the failure plane multiplied by the tangent of the internal angle of friction of the material at the failure plane. The stability against failure is governed by the thickness and strength of the fill.



1. Slope Failure/Edge Failure
2. Truncation Failure
3. Bottom Sliding Failure

Figure 7.18 Potential Failure Planes/Modes for Causeway

Bottom Sliding Failure:

Sliding failure is considered unlikely since failure through the seabed requires a higher lateral force than failure through the island.

Slope Failure/Edge Failure:

The force resisting upward passive failure is:

$$Rs = Ht\,\gamma\,(1 + \cot\theta \tan\phi) + P_H \sin\theta \tan\phi + 1.41\,\tau_f\, t \cos(45^\circ - \theta)$$

where:

Rs = resisting force

H = island freeboard height

t = thickness of frozen fill

γ = unit weight of frozen fill

ϕ = friction angle of frozen fill

θ = island side slope angle

P_H = horizontal ice pushing force

τ_f = shear strength

Once the island fill is frozen, failure of the slope is considered unlikely since the frozen saturated fill of the island is generally much stronger than the surrounding ice.

Truncation Failure:

Truncation failure is possible only when the upper portion of the island is frozen and acts as a rigid body. Since the fill material gains strength as it freezes, the failure plane within the fill will be located at the frozen/unfrozen interface. The force resisting truncation failure is:

$Rs = W \tan \phi$

where:

Rs = resisting force

W = total effective weight of the fill above the failure plane

ϕ = friction angle of the island fill

The failure plane is assumed to occur approximately at the bottom of the ice sheet. The analysis of other failure planes would produce a similar expression.

Forces Due to Impact of Large Ice Floes and Icebergs on Gravity Structures

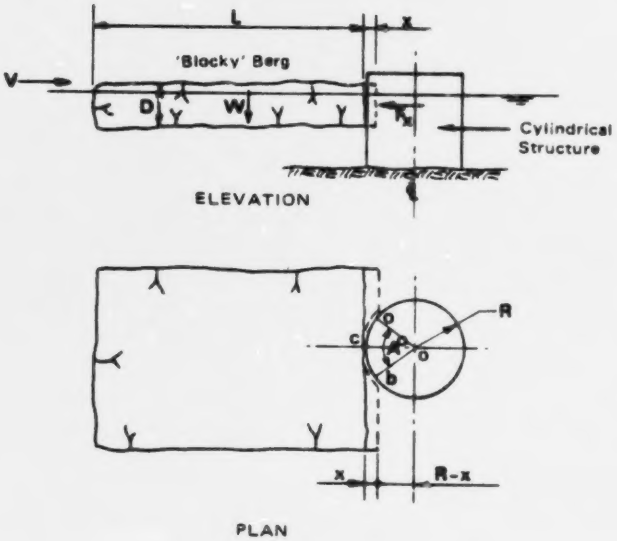
The force due to impact of large ice floes or icebergs on a gravity structure can be computed from the energy equation which relates the kinetic energy of the ice floe or iceberg with the energy dissipation due to progressive crushing of the ice. When a large ice floe or iceberg collides with a gravity structure, the contact zone will fail by crushing and the contact area will increase as the resisting force is steadily built up. The kinetic energy is absorbed until an equilibrium point is reached.

Equations have been developed by A.B. Cammaert and G. Tsinker ("Impact of Large Ice Floes and Icebergs on Marine Structures", Volume 2, Page 269) for the case of a "blocky" iceberg colliding with either a cylindrical or conical gravity structure. For a cylindrical structure, the equations are: (Figure 7.16 and 7.17).

$$X_m = \left(\frac{0.198\, W_1\, V^2}{D\, f\, R^{1/2}\, g}\right)^{2/3} \text{------------------------------------} \quad (8)$$

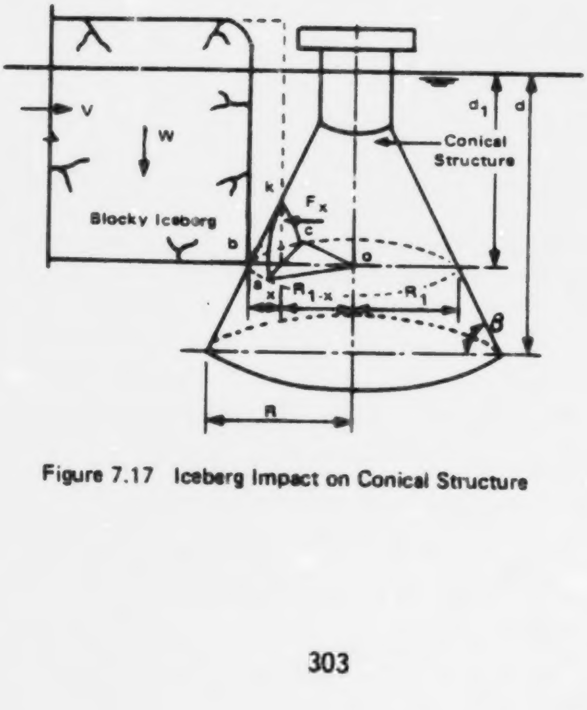
$$F_m = 2\, D\, f\, (2R\, X_m - X_m^2)^{1/2} \text{-------------------------------} \quad (9)$$

For a conical structure, the equations are: (Figure 19)



L
x
'Blocky' Berg
V
D
W
F_x
Cylindrical Structure
ELEVATION
R
c
a
o
b
x
R-x
PLAN

Figure 7.16 Iceberg Impact on Cylindrical Structure



V
W
d_1
d
Conical Structure
k
F_x
c
Blocky Iceberg
b
o
a
x
R_{1-x}
R_1
β
R

Figure 7.17 Iceberg Impact on Conical Structure

$$X_m = \left(\frac{0.50\, W_i\, V^2}{\tan B . f . R^{1/2} g}\right)^{2/5} \text{------------------------------------} (10)$$

$$F_m = \frac{4}{3} \tan B . f\, X_m\, (2R_1\, X_m - X_m^2)^{1/2} \text{-----------------------} (11)$$

where:

X_m = maximum penetration or indentation, m

F_m = maximum impact force, kN

W_i = iceberg displacement weight, kN

V = iceberg velocity, m/s

D = iceberg depth , m

f = ice crushing strength, kPa

R = structure radius at base, m

g = acceleration due to gravity, m/s^2

B = cone angle

R_1 = structure radius at point of impact, m

The structure stability should be checked for sliding and overturning, due to the maximum impact force. The structure strength against local contact pressures during crushing should also be verified.

7.5.2.4 Floating Structures

This section deals with the design of floating structures, such as ice booms and barges. Oil and gas drilling platforms are not included in this discussion.

The design information in the section has been synthesized from the paper on "Design of Submerged and Floating Structures for Ice Forces" by P.G. Noble - Volume 2, Page 289.

Floating Ice Booms

Generally, in non-arctic areas, ice booms have been used to assist nature in quickly forming a solid ice cover on rivers. The open water, insulated in this way, is no longer the source of frazil ice which, in the past, has caused ice jams, flooding, and the loss of electrical generating capacity. They function in other ways as well, strengthening the ice sheet edge against subsequent damage and restraining its movement.

Ice booms are basically lines of floating timbers or pontoons held in place by heavy cable structures connected to buried anchors. They were developed and are used mainly by hydroelectric power groups but they also help facilitate ship navigation in winter. The general details of an ice boom are shown in Figure 7.19. In operation, the floating barrier restrains the ice floes and the resultant load is transferred to the cable structure and ultimately to the anchors. The anchor cables extend upstream and slope downwardly in that direction at a shallow angle. This lets the booms submerge if the ice forces become too great, as they often do during spring ice break-up.

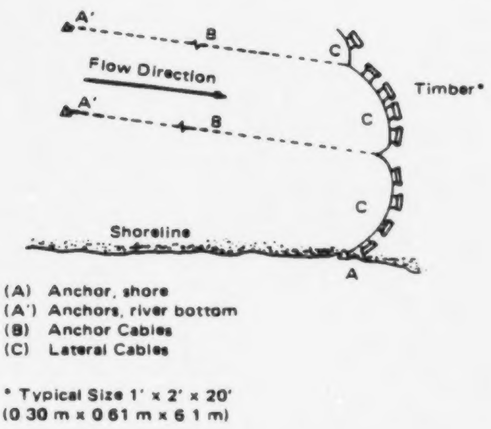


Figure 7.19 Typical Ice Boom

The floating portion of the ice boom is designed to sag downstream a certain amount. The cable length is often twenty-five or thirty percent greater than the span to reduce the load in the cable. A secondary benefit of this feature arises when an anchor is inadvertantly displaced and the movement can be absorbed by the slack. Anchors used in mud and clay sometimes readjust their position under load.

The anchors used underwater are of three general types, rock anchors, clay or mud anchors and pile clusters. The piles are used in materials of intermediate strength between rock and mud or clay. The rock anchors are usually set in holes drilled deep into the bedrock. One type is a large chain that is suspended in the hole and then fixed in place with concrete. The chain links allow the direction of the anchor load to change without twisting the anchor. The shore anchors are usually of the buried "dead man" type.

High strength steel wire ropes are used for the structure. Bridge cable has been used in some locations, for example, on Lac St. Pierre in Canada, but generally construction wire rope is easier to handle with conventional equipment. The cables are interconnected by wire rope fittings and heavy steel junction plates. These structural components require that floats be added to keep them from sinking the booms.

Many of the booms, or floating barrier units, are made from Douglas Fir and are roughly 2.0 ft x 2.0 ft x 20 ft or 30 ft (0.3 m x 0.6 m x 6.0 m or 9.1 m) in size. The general scarcity of large sizes of this wood has led to at least one case of making them from metal. Steel pontoons 1.3 ft x 2.5 ft x 20 ft (0.4 m x 0.8 m x 6.0 m) have been built for ice booms on the Riviere des Prairies north of Montreal. Sometimes two or more pieces are used in parallel.

Except for handling forces, the load P on the ice boom comes from the ice cover behind it which is continually acted upon by natural phenomena. In simplest terms, after Berdennikov:

$$P = Q + D + W + G + I + F$$

Where:

Q = hydrodynamic force at the upstream edge of the ice cover

D = frictional drag of water flowing beneath the ice cover

W = frictional drag of air flowing above the ice cover (τ_a x ice area)

G = downstream component of the weight of the ice cover

I = impact force of collecting ice floes

F = frictional force or the shearing force from the shore line

Each of the above terms has significance according to the physical conditions applied and Q, G, and I can often be neglected.

The drag force, D, depends upon the roughness of the underside of the ice cover and upon the mean velocity of stream flow. The underside of the ice cover and the stream bed form a hydraulic conduit and the Manning roughness factor n is generally used to describe its roughness. Equations have been developed to distinguish between stream bed roughness and ice cover roughness althougn the two are sometimes the same. Michel gives an approximate range of roughness values for ice cover of 0.013 to 0.09. Generally, ice is rougher in early winter and smoother later on.

The intensity of shear at the boundary of a conduit in uniform flow can be expressed as

$$\tau_0 = \frac{1}{4} \frac{fV^2}{2}$$

where f is the Darcy-Weisbach coefficient, and V is the mean velocity relative to the boundary or the ice cover in this case. The Manning number n is related to f through flow considerations as

$$\frac{1}{\sqrt{f}} = \frac{1.49 R^{1/16}}{\sqrt{8g\ n}}$$

where R is the hydraulic radius of the conduit and the factor 1.49 has the dimension of $\sqrt{g}$. Combining the above equations yields

$$\tau_0 = 0.45\ nR^{-1/3}\ \rho V^2$$

For a median value of $n = 0.051$, $V = 2.25$ ft/sec (0.69 m/sec), R=e 17 ft (5.2 m), $\rho g = 62.4$ lb/ft^3 (999.6 kg/m^3), and $\tau_0 = 0.14$ m lb/ft (6.9 Pa). The force, D, is the product of τ_0 and the ice area. Under the above conditions 0.5 square mile (1.3 km) of ice would be loaded by nearly 2.0×10^6 lbs. (8.9×10^6 N).

The force, F, due to friction at the shoreline acts to hold the ice cover back. As the individual floes are restrained by the ice boom they push against each other in response to flow forces. Because of their irregular, but generally rounded, shape some of this push is exerted laterally. The floes are restrained from moving laterally by the river banks. There exists at this time of year a coefficient of friction between the cover and the bank and F is the product of this coefficient and the bank force.

Latyshenkov conducted a test of ice boom forces in a small power canal with parallel sides. His results showed that these frictional forces were cumulative in an exponential manner such that after the cover length was greater than 2.5 to 3 times the canal width, the cover no longer needed support from the boom. The ice in effect is jamming but in a two dimensional manner only and, in the case of ice booms, this is helpful.

Under average conditions the ice during spring break-up can act with much greater force on the boom. The broken ice pieces are much larger and, responding to the added influence of meltwater, they move with greater momentum and drag force. According to Pariset the retarding effect of the shoreline (friction) which previously aided the ice boom now practically disappears. The ice boom generally will sink under excessive loads and let the ice slide over. Occasionally, the ice and boom and structure will entangle to the extent that very high loads are developed. Forces over 300,000 lbs (1.33×10^6 N) have been measured in anchor ropes. It is not uncommon for 0.88 inch (2.22 cm) chains and large timbers to be broken.

Floating Plant Barge Frozen-In

This example takes into consideration the ice loads applied to a barge frozen into a pool or protected dock area. The ice loads applied to the vessel result from thermal pressure due to the abrupt changes in air temperature and/or the wind induced force of moving ice floes. In order to predict the forces or stresses that might occur, it is necessary to have information not only on the properties of ice, but also on the actions between the ice and the barge.

Static thermal ice pressure exerted on the barge will develop due to a rise in temperature of the ice cover, when its free expansion is obstructed by the shore or the structure. This thermal ice action acquires maximum significance for the design of a barge subjected to climatic conditions typified by abrupt fluctuation in air temperatures, and hence ice temperatures.

The deformation of ice has a complex dependence on a number of factors, including temperature and structure of ice, duration of effect, nature of load and the state of stress in ice. In addition, the local conditions like the configuration and nature of the shoreline also have a tremendous influence.

Because of insufficient knowledge on this mechanism, there is no accurate method of determining the thermal pressure. However, empirical equations have been developed by various investigators in this regard.

Korzhavin suggested an empirical equation of the form:

$$P = 3.1 \frac{(T_i + 1.0)^{1.67}}{T_i^{0.88}} \theta^{0.33}$$

Where:

P = thermal pressure in t/m

$T_i = 0.35\ T_A$

$\Theta = 0.35\ \Delta T_A/t$

T_A = mean air temperature in °C

ΔT_A = rise in air temperature (°C) during time (hrs.)

Values for the thermal ice pressure (P) were calculated for various initial ice temperatures and different rates of increase of air temperatures. The results are depicted in Figure 7.20. The general design values used by Canadian engineers vary between 4.53 to 6.80 tons per foot (14.87 tons/m to 22.31 tons/m) for rigid structures, such as concrete dams, and for flexible structures it is 2.27 ton/ft (7.44 tons/m). Korzhavin states that values between 0.5 to 2.8 tons/ft^2 (5 to 30 tons/m^2) are used in the U.S.S.R. For a completely restrained condition, a value as high as 5.6 tons/ft^2 (60 tons/m^2 is used. For an ice cover 6.6 ft (2 m) in thickness, the design values vary between 0.8 and 9.1 tons/ ft (2.5 to 30 tons/m).

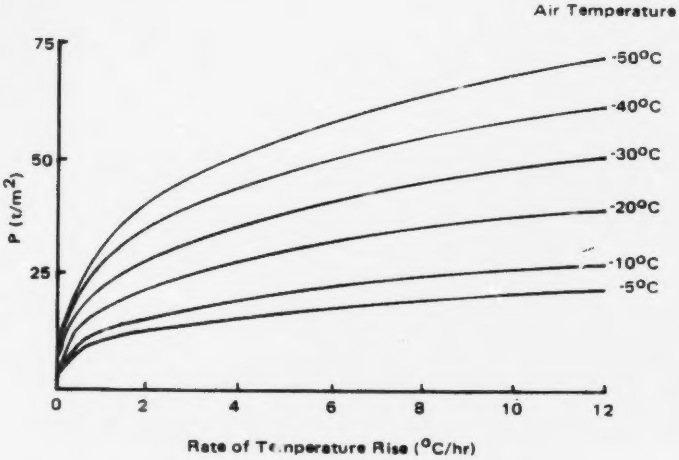


Figure 7.20 Thermal Ice Pressure

Wind blowing along the ice surface induces a force which tends to move the ice cover, which in turn exerts pressure on the barge. This wind induced ice force depends on a number of factors like wind speed, surface texture, and the ice cover area. Danys suggested an equation for the force exerted by the wind against ice cover in the following form:

$$F = 0.132\ C\ U\ A\ (N)$$

Where:

C = drag coefficient (1.6×10^{-3} for normal snow covered ice)

U = wind speed in m/sec

A = surface area of ice cover in m

The pressure acting on the hull of the barge through the ice cover can then be expressed by:

$$P_w = F/Bh$$

Where:

P_w = wind induced ice pressure, kPa

B = contact length, m

h = ice thickness, m

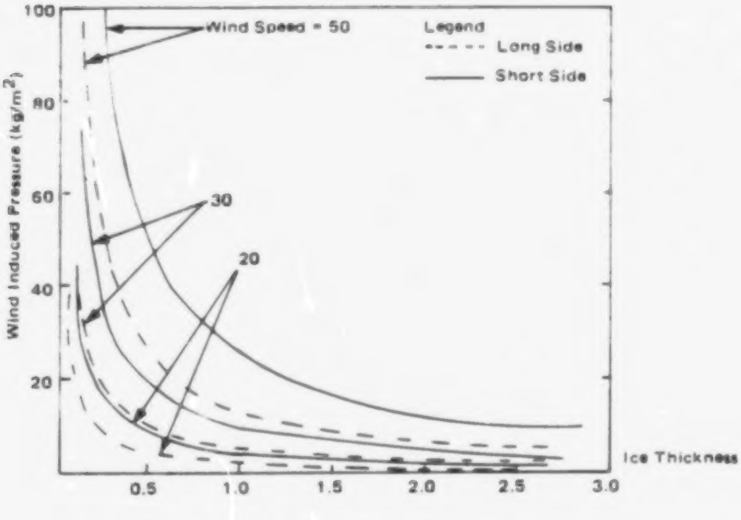


Figure 7.21 Wind Induced Ice Pressure

Values of wind induced ice pressure acting on a 485 ft (148 m) long barge have been calculated for various wind speeds and ice thicknesses, for a dock area of 430,000 ft^2 (400,000 m^2). The computed results are plotted against the ice thickness as a function of wind pressure (Figure 7.21).

It can be seen that for restricted dock areas the thermal ice load dominates and conversely other estimates could be made to show that, when frozen into an extensive ice sheet, the wind induced loads would become more significant.

7.5.3 Fender Systems

7.5.3.1 Energy Calculations

There are no firm recommended practices for fender system design. In designing such a system, an estimate of berthing energy should be made such that it is adequate for normal operations, is economical and is one that can be installed without undue difficulty.

There are two methods used in estimating the berthing energy on the fenders. These are the conventional method and the statistical method.

Conventional Method

This method is the most frequently used, and is based on a theoretical kinetic energy formula

$$E = \frac{1}{2}\frac{W}{g} V^2 C_e Ch \ C_c C_s$$

where:

E = Kinetic Energy, kW

V = Ship's Approach Velocity (normal to pier), m/s

W = Ship's Displacement, kN

g = Gravitational acceleration, m/s^2

C_e = Eccentricity Coefficient

$$C_e = \frac{a^2}{a^2 + r^2}$$

r = radius of gyration about the vertical axis of ship in a horizontal plane

a = distance from point of contact to the centre of gravity of the ship.

The impact point is frequently assumed as .25 of ship's length where $C_e \equiv .5$

C_h - Hydrodynamic mass coefficient

$$C_h = 1 + \frac{2D}{B}$$

D = Ship's draft

B = Beam

C_c - Configuration coefficient

C_c = 1.0 open pier

= .9 semi-closed pier

= .8 closed pier

C_s - Softness coefficient to allow for energy absorber

In the absence of more accurate data ship's approach velocity may be taken from Figure 7.22.

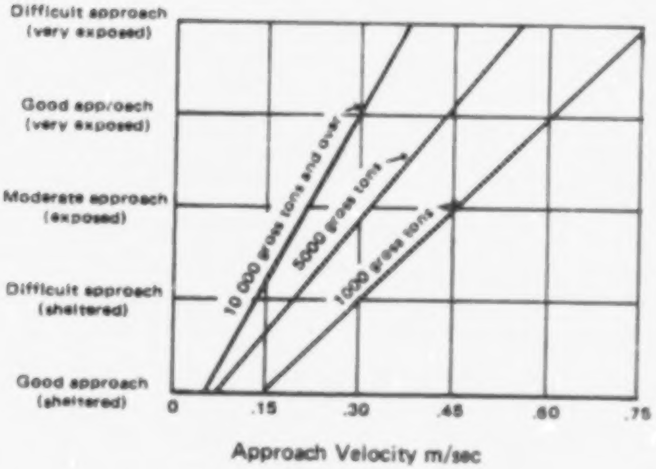


Figure 7.22

Statistical Method

Dent and Saurin (reported by P.J. Piaseckyi in paper presented at 24th International Navigation Congress) recommend that for a berth exposed to moderate wind and waves as well as a moderate approach to berth, the following energy values should be used:

2.3 m-t/1000 DWT - at yield stress in fenders

1.6 m-t/1000 DWT - at working stress in fenders and breasting structures.

For berths located in protected harbours 5/8 of the above figures are recommended. For exposed locations, however, it would be prudent to increase the above values by 50%.

Depending on the location and exposure in the harbour, berthing of vessels in the arctic region may not differ much from the berthing operations in other harbours. However, because of the remoteness of arctic locations, and usually non-existent tug assistance, it is prudent to adopt a conservative approach in estimating the berthing energy.

One additional factor which may significantly influence Fender design is the impact of large ice floes on the outer side of vessel moored to wharf. This design feature was considered at the Hadlow Cove Golden Eagle Wharf project.

7.5.3.2 Wharf Fender Types

The main consideration in selection of the type of fenderings for the installations in the arctic regions should be potential ice action and damage to fender systems. Pile supported fender systems, or fender units mounted within tidal or ice-affected zones should be avoided, since such fenders are subject to ice damage and would likely be costly to maintain.

The most practical approach has been found to be a removable or retractable fender system which can be readily placed in position for the duration of the navigational season, or in extreme conditions can be positioned for each berthing.

In areas where tides are small it may be possible to mount Rubber Fender Units above the ice-affected zone.

In areas of large tides the most practical solution was found to be Floating Pneumatic Fenders. Such fender units have been successfully used for the dock installation at Deception Bay and Hadlow Cove, Quebec. A substantial overload capacity is available utilizing this type of fender which makes it attractive for arctic locations.

Apart from the above considerations, the selection of the fenders and attachments for arctic installations utilize the same engineering principles as those used on marine installations in ice free harbours. However, because of the remote locatons of the arctic installations, short navigational season and high cost of repairs, it is prudent to provide larger than normal overload capacity in the fendering system in order to allow for minor accidental berthing impacts without significant structural damage to the wharf.

7.5.4 Corrosion

In general, corrosion of steel in cold regions is less severe than in moderate or warm climates, therefore, only a brief account of the corrosion processes and mitigation techniques are presented here. For more detailed account the reader should refer to available technical literature on this subject.

Corrosion Process

All steel structures in marine environments are subjected to corrosion. The corrosion process primarily involves the steel, and an electrolyte, in this case sea water, and oxygen. As a result of the corrosion process iron oxides are formed on the surfaces of steel structures.

A number of factors influence the rate at which the corrosion process proceeds. These are:

1) Water temperature
2) Concentration of oxygen in sea water
3) PH value of sea water
4) Marine fouling organisms
5) Salinity of water
6) Velocity of water
7) Galvanic effect of unlike metals.

7.5.4.1 Corrosion Zones

Corrosion evaluation of steel piling is usually considered with respect to five zones as follows:

1) Splash zone - extends from the deck down to the high water level

2) Inter-tidal zone - includes the area from high water to just above low mean water

3) Low water zone - approximately 1.0 m above to 1.0 m below low mean water

4) Underwater zone - extends from 1.0 m below mean water to the mud line

5) Mud zone - extends down from the sea bottom.

Corrosion Rates

In the absence of more specific information the following corrosion rates may be used in estimating service life of the structure and in calculating corrosion allowance for steel material.

	Corrosive Environment	Corrosion Rate (mm/year/Surface)
Sea Side	Splash & inter-tidal zone	0.3
	Low water & underwater zones	0.1
	Mud Zone	.03
Land Side	In marine atmosphere	0.1
	In Soil - above water level	0.03
	In soil - below water level	0.02

7.5.4.2 Anti-Corrosion Protection

Methods presently used to mitigate the corrosion of steel structures in sea water include the encasement of steel in concrete (jacketing), the application of various protective coatings, cathodic protection and various combinations of these methods.

Another method of combating corrosion damage to steel is a sacrificial one, which involves increasing the wall thickness of the metal to allow for a pre-determined rate of corrosion.

Selection of the type of protection will depend on the environmental conditions of the site, areas to be protected (corrosion zones), service life of the structure and the normal practical and economic considerations.

Present day experience indicates that the most practical approach to provide for useful life of a structure, in the arctic environment, is to design corrosion allowance into the structure.

The rationale for this conclusion is:

a) Rates of corrosion in cold regions are lower than in warmer climates, hence corrosion allowances are within economic limits.

b) Protective coatings are easily damaged by ice action.

c) Cathodic protection requires maintenance to ensure the continuity of protection. In addition, concrete jacketing in the splash and tidal zones would be required. Such jackets, in case of pile construction, would result in an increased force on the structure.

d) Installation of corrosion protective systems would introduce additional construction activity in an already very short arctic construction period.

CHAPTER 8

CONSTRUCTION PROCEDURES AND TECHNIQUES

8. CONSTRUCTION PROCEDURES AND TECHNIQUES

While a wealth of information has been published on the design of arctic marine structures, there is a paucity of published information on the construction of these structures. The reason may be that arctic construction is a competitive business and contractors having such arctic construction experience consider this information as classified corporate commercial data.

A good example of an arctic project is found in published information on the Asbestos Hill Process Plant, storage building and wharf facilities at Deception Bay, Quebec. Reference papers are:

- "The Asbestos Hill-Nordenham Story - Engineering and Construction of Plant and Wharf Facilities", by F.S. Thurner, The Canadian Mining and Metallurgical Bulletin, November 1976 (Volume 2, Appendix 2).
- "Asbestos Hill Report" by E. Romer in Foundation Bulletin, 1972 Review (Volume 2, Appendix 2).
- "A cold region Canadian port development", by T.F. Saunders (Volume 2, Page 297).

Other interesting examples are: the construction of the Strathcona Sound Wharf at Baffin Island which is described in POAC 1977, and the construction of the Cominco Wharf at Little Cornwallis Island is the subject of a short documentary film available from Tower-Arctic Ltd., Montreal.

In addition, useful papers on arctic construction are "Facilities, Development, Construction and Operation Problems and Related Environmental Conflicts and Problems of the Ice-Stressed Coastal Areas of Alaska" by Bretschirder, Sargent, Doyle and Shandtman, POAC, 1971 - Volume 2, Appendix 2. "Artificial Islands and Steel Structures in the Beaufort Sea" by Maxwell, McGonigal and Graham (Volume 2, Page 284).

The material in this chapter has been synthesized from information in the above publications and interviews with construction specialists having hands-on experience in arctic construction.

8.1 Construction Planning and Scheduling

In addition to the usual considerations for planning and scheduling construction of a marine structure in the south, construction of a marine structure in arctic regions must recognize the severe constraints exerted by the climate and remoteness of the region.

The logistics of transporting materials, equipment and personnel pose difficult problems. Because of this, available on-site construction material should be exploited as much as possible and materials imported from off-site should be kept to a minimum. Also, pre-assembly and pre-fabrication of construction units should be maximized. Where structures are pre-built in the south and towed to location in the north, the towing and setting down operations must be carefully planned and executed.

Construction scheduling must recognize that the installation be accomplished rapidly since in many arctic areas, the installation window may be restricted to only a few weeks. It is important to complete the structural installation on time since partially completed systems are vulnerable to ice damage. Allowance must be made for arctic storms which often cause all construction work to cease. At such times survival activities assume top priority and pre-empt all other activities.

In general, construction productivity during December to March is only a fraction of that obtained in the south. Informed decisions are required as to whether or not construction programs should be scheduled during this period.

Some key activities for construction planning and scheduling of Arctic marine structure are:

- compare consequences of alternative start dates
- establish start date
- compare consequences of construction by season
- carry out sensitivity analysis to determine most cost effective construction method, and
- modify design if original design does not permit economically attractive results. Analysis should indicate how sensitive scheduling and costs are to external environmental events.

8.2 Environmental Criteria

The environmental conditions pertaining to a particular site in the Canadian arctic may be obtained from Supplement No. 4 of the National Building Code. Additional information may also be obtained from the Meteorological Department of the National Research Council. Additional references are identified in Chapter 2 of this Handbook.

The proposed design and construction method should be examined with respect to probable environmental impact on sea bottom and water quality (short and long term).

8.3 Construction Techniques

There are several principal construction techniques presently adopted for arctic construction which differ from southern conditions. These construction techniques have evolved from experience gained in arctic construction. The location and types of structures utilized on previous projects are identified in Chapter 9 of the Handbook.

For example, the steel sheet pile cells in Baffin Island and Little Cornwallis Island were constructed using the ice sheet as a working platform. Where the natural ice sheet is not thick enough or strong enough to support pile-driving and other construction equipment, the ice can be built up to the required strength and thickness by artificial flooding. Design guidelines are presented in Chapter 7 and relevant publications in Volume 2.

At Little Cornwallis Island, the natural ice sheet thickness of about 5 feet (1.5 m) was increased to 9 feet (2.7 m) by artificial flooding. This was sufficient to support construction equipment. An external template was used to position steel sheet piles consisting of a single ring of timber and steel waler, approximately 1 foot high. It was made of bolted segments and laid on the ice in its correct position. Using a three foot chain-saw, the ice was slotted to receive the steel sheet piles. The slot was prevented from re-freezing by using a non-pollutant oil in the slotted section.

In a conventional template used for construction of steel sheet pile cells in the south, there are usually two circular walers spaced about 10 feet (3.0 m) apart vertically with spud-piles inside the cell to support the template. The upper waler is a necessity as a template, the lower waler helps to keep the sheet piling plumb. In the case of an ice-sheet platform, if there is no current to contend with it appears that a single ring waler is all that is needed. Care must be taken to have the first pair of piles plumb as they are toed into the bottom. A similar method is used for constructing the arc-cells.

At Deception Bay, the ice sheet could not be utilized as a working platform to drive the piling because of tides in the range of 20 feet (6.1 m). Tidal action continuously broke up the ice-sheet in the area of the wharf site. This caused hinge-action to develop and unstable ice surface conditions*. A conventional 2-waler template was adopted at Deception Bay and both the spud piles the sheet piles were driven into a previously placed 10 foot (3.0 m) gravel mattress which provided initial lateral support for the piling.

A significant factor with this type of construction is to remove all ice from within the cell before filling. If ice-blocks or ice-lenses are buried with the cell fill, sink-holes and overall settlement will occur in the cell fill during the thaw periods when the ice melts within the cell.

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* This required the wharf construction to utilize the limited ice-free period which at Deception Bay is about three months.

For those portions of a arctic marine structure that is scheduled to be constructed in the ice-free conditions, the construction methodology adopted will not be very different from that adopted for similar construction in the south. For example, the causeways connecting the cells to shore may be constructed using conventional earth and rock moving equipment.

Some construction procedures and techniques which have proven effective are as follows:

- Use land based construction equipment
- Minimize utilization of heavy marine plant
- Utilize sea ice as construction platform
- Plan construction activities to avoid thawing of permafrost
- Construct access of grave berms above surrounding ground to assist in snow removal by wind
- Drainage culverts to be large enough to be maintained free of ice or snow, irrespective of hydrology demands
- Steam jetting of piles into permafrost soils.

8.4 Material Selection

Because of remote location and attendant logistic problems, arctic marine structures should exploit the use of available on-site construction materials as much as possible. Refer to Chapter 4 of this Handbook. Conversely, imported construction materials should be minimized as far as practicable.

8.4.1 On-Site Materials

Dredged sand from the sea-floor is suitable for the construction of berms and islands as well as for filling steel sheet-pile cells or concrete caissons. This material is available over extensive areas in the North American arctic particularly in the Beaufort Sea and has been used in the construction of many Beaufort structures as hydraulically placed sand-fill. The most favourable borrow sources are east of 133.5° longitude, where areas with negligible overburden are common. Small deposits of granular material, (probably beach deposits left during the sea level rise) do exist but are difficult to find. Sand and gravel were taken from such a location, named Issigak, to construct part of the Tarsiut berm.

Sand deposits are reasonably close to exploration sites in the eastern Beaufort. In order to construct islands and berms in the western areas, sand must be barged up to 100 km. In addition, more borrow material is required to replace the layer of soft foundation soil which is removed. The cost of constructing a berm in the west may be 3 to 5 times the cost near the borrow sources in the east. The use of caisson structures to reduce borrow quantities or gravity containment should be carefully considered.

Another method of reducing borrow volumes is to steepen the side slopes. Sand has been placed hydraulically with sideslopes between 5H:1V and 20H:1V, whereas gravel could be placed at 3H:1V. Subsea gravel borrow is very rare. Sources are thought to exist near Herschel Island, further west, however significant quantities have not been substantiated. Fill for some of the Esso Resources earlier islands consisted of gravel trucked over the winter ice from inland borrow pits.

Armour materials from quarry rock are available from inland pits near Inuvik. Processing, transportation and placement of this material is very expensive. As an alternative, Esso Resources has used large sand filled bags to provide erosion protection for exploration structures of short life. Because of the scarcity of gravel and riprap, concept designs for longer life production structures, are now minimizing the usage of these materials with caissons or man made alternatives such as cement blocks, sand asphalt, or reinforced sand.

Ice itself can be used as a construction material. By repeated flooding and freezing in layers, any natural ice-sheet can be thickened sufficiently to be utilized for supporting a particular load. It has been demonstrated during World War II, and later at the University of Alaska, that a saturated wood pulp or sawdust, when frozen, made a suitable and durable building material.

Certain structures can be built in the arctic by utilizing a frozen well-graded saturated gravel. This results in material having acceptable strength characteristics. Such materials are sometimes referred to as "ice-crete". The "ice-crete" material can be kept frozen by insulation, using either a manufactured insulation, sawdust and ice, ground tundra moss or grass and ice.

8.4.2 Offsite Materials

Any materials brought in from offsite can increase the problems of transportation and hence should be kept to a minimum, both in terms of weight and volume.

The major construction materials imported from offsite are usually steel, cement and timber. Prefabrication should be exploited as much as feasible. Also, preassembly of components should be carried out to the maximum extent possible considering transportation capacity. To minimize weight volume, high strength steel and concrete should be utilized, including light-weight concrete.

The technique of building with plastics that can be imported as liquids, and later foamed and expanded, could be very useful.

In addition to construction materials, consumable materials need also be brought in from offsite. A large proportion of consumable materials is likely to be fuel.

8.5 Equipment Selection

Generally, there is very little specifically designed construction equipment for operation in the arctic. Construction equipment which operate in the south, can generally be adapted for service in the arctic. However, special lubricants and fuels developed for arctic conditions should be used, as well as special maintenance procedures to minimize downtime. These are generally covered by the manufacturer's specifications or Operating Manuals.

- Utilize only equipment with proven reliable operating characteristics. It should be new or completely refurbished. Construction delays caused by equipment failure are very costly.
- Specialized equipment is now available for drilling in ice and permafrost soils and for cutting or excavating this material.
- Information concerning maintenance and operation of construction equipment in Arctic conditions is available (Volume 2, Chapter 6.0).

Regarding arctic shelters, several types are available on the market, which are especially manufactured for arctic service conditions (Volume 2, Chapter 6.0).

8.6 Labour Supply

The permanent native population of the arctic area is small and scattered in villages and tribal settlements. The native peoples especially the young, can be and are being trained in construction trade skills. They are inherently acclimatized to conditions of life in the region and should be utilized whenever possible. However, at the present time, there is a substantial deficiency in numbers of trained Innuit available for construction purposes at any one site.

At Deception Bay, it was initially planned to have a project agreement with the unions and to have the job protected under such agreement. Application was therefore made by ACL (the Contractor) for the negotiation of such an agreement before the contract award. However, at that time, renegotiations of the Montreal agreement with the unions and construction associations were in progress and a separate agreement for the Asbestos Hill Project, at Deception Bay, could not be formalized and therefore the project had to use the Churchill Falls agreement until the end of 1970.

On January 1, 1971, the new decree came into effect which established labour and pay conditions for the construction industry throughout the Province of Quebec. The new law obligated every construction worker to be a member of the labour association *union) and also to be properly registered and have a work permit from Quebec Manpower. The Minimum Wage Commission, later renamed the Construction Industry Commission, was empowered to supervise the decree and act as arbiter between the labour association and contractors.

There were several problems in the interpretation of the new decree and, in particular, the application of the regional wage scales. This was the first time that a remote project in the Arctic came under union jurisdiction.

The labour regulations which govern Arctic projects is the Canada Labour Code for Federal projects only. Labour regulations for Northwest Territories govern other projects and oil companies conform to the Alberta labour codes.

8.7 Logistics

The remoteness of the arctic site location and the limited means of transportation available make logistics of arctic construction a factor of prime importance.

The following account of sealift operations to Deception Bay represent a typical arctic project.

Sea transportation to Deception Bay was limited to a 3-month duration per year, with the first ship leaving Montreal on July 15 and arriving at Deception Bay about 12 days later. On the return voyage, ships had to leave Deception Bay not later than October 23. These rigid deadline dates were set by insurance policies for ships navigating in Arctic waters. Although early and late shipping was possible within reasonable limits, they were not dependable and carried heavy additional insurance premiums.

This limitation of the shipping season made it imperative that project orders be placed early, with special arrangements to secure deliveries. The materials and equipment which missed the last boat in October had to wait until the following year in July, before delivery. For the first shipment season in 1970, it was therefore necessary to arrange for deliveries of equipment and materials required not only for the first construction season, but also for all those necessary for the spring and early summer of 1971. With the last ship of the season leaving Montreal around mid-September, this meant that after 4½ months from the award of the construction contract all material and equipment required for half of the total construction activities had to be designed, procured, fabricated and delivered to the port of Montreal.

This necessitated short cuts, having to work from preliminary drawings, and facing field modifications and revisions. This factor also played a decisive role in subcontracting the detail design, fabrication and erection of the fibre storage building to AMFAB Products Ltd. This building was designed to store 230,000 tons of coarse asbestos fibre and AMFAB accomplished the seemingly impossible task of designing, fabricating and delivery of over half of the structure, representing over 1 million board ft of laminated glued wood, within 2½ months from the date of their contract award.

Similarly, Central Quebec Steel, suppliers of the structural steel, delivered approximately to 1,000 tons of fabricated structural steel by the end of the first shipping season.

During the two shipping season in 1970 and 1971, a total of 16 ships were dispatched to Deception Bay carrying a total cargo of 22,000 short tons.

All sealift operations were carried out by Maritime Agency Inc., of Montreal, and their contract included the unloading of cargo into barges with the towing of the barges to the beach. The unloading of the barges and the storage of the material was the responsibility of the joint venture.

The shipping activities went on without serious problems until the unloading of the last ship of the shipping season on November 2, 1971. The last barge from the last ship, with 150 tons of equipment and materials, overturned and the entire cargo sank in a depth of 160 ft of water. The effect of this accident was a disaster. There was no way of salvaging the cargo from the bottom of the bay or to wait for refabrication and shipment during the following shipping season in the summer of 1972. As the lost material consisted of fabricated parts for conveying equipment, some process machinery and some structural steel, these had to be refabricated and flown to the site to meet the required completion date of the facilities.

Handling and Storage of Materials

Without suitable wharf facilities for the berthing and the unloading of the cargo ships, the handling and storage of materials and equipment resembled a military operation. Ships had to be anchored in the bay, their cargo transferred to barges and the barges towed by tugs to the shallow sandy beach, which was close by and had relatively good access to the roads of the two construction sites. The barges were beached and unloaded when the water subsided at low tide.

8.7.1 Transportation of Material and Equipment to Site

Sealift remains the least expensive and most effective mode of transportation in the arctic. However, much of the arctic coast of North America is ice-bound for about 9 months of the year, resulting in difficult scheduling problems of arctic supply vessels. In addition to being ice-bound, the northerly sea has many shallow areas with many shoals and barrier islands, on most approaches to land. There is at present, no vessel powerful enough to negotiate the ice-pack and with shallow enough draft to negotiate the approaches to existing port sites. At the present time, it appears that the system of using ships and sea-going barges in great numbers, during the few weeks when the ice is out, is the only practical method of transporting materials and equipment to the arctic.

Some companies providing transportation services in the Canadian Arctic are listed in Volume 2, Appendix 4.

8.7.2 Transportation of Personnel to Site

Air transportation can serve practically the entire arctic area during most of the year and is effectively doing so now. However, due to of the cost of air operation, air transport is and probably will continue to be predominantly passenger and mail-carrier service. Only high priority consummables, materials and equipment will be flown in.

Air transportation of construction equipment and materials is obviously limited by weight and size. Any oversize shipment requires either a special aircraft or can not be airlifted at all. For example, at Deception Bay, a special aircraft was chartered from Edmonton for the transportation of an urgently needed extra section of boom for a 110 ton crane. In another emergency, the replacement of a broken crane boom was airlifted in pieces and assembled on site. The following account of airlift operations at Deception Bay should be typical of most arctic projects of this nature.

Air transport was the only permanent lifeline for maintaining contact with the site. It covered the transport of all men in and out, all perishable food supplies, mail and all emergency supplies (mostly spare parts) which could not be shipped by sea.

During 1970, operations were restricted to charter flights only. Regular scheduled flights twice a week to Deception Bay, by Nordair Limited, from Montreal and servicing the north with scheduled flights to various Arctic destinations, were only introduced in April 1971. The charter flights were not dependable, as in some instances the aircraft was not available and on other occasions the cargo was insufficient to justify the flight. Also, when the charter flight was unable to land at the site due to weather conditions, it would be aborted to Frobisher Bay. It was then the contractor's responsibility to charter another aircraft, resulting in additional expenses to have the cargo and the passengers flown to the site. Six flights out of a total of 44 charter flights were aborted.

During the scheduled airline operations, a special cargo rate was secured based on a guaranteed minimum weight of 800,000 lbs per year. Under this agreement, it was the airline's responsibility to deliver the cargo to the destination regardless of stopovers or the necessity of secondary shuttles.

The operation of flights to Deception Bay was very vulnerable and subject to weather conditions and poor communications. Without any landing and approach facilities, except for a single beacon, the pilots had to depend on visibility and moderate winds.

Throughout the two years of operation, a total of 3,800 passengers were flown into and out of the site at an average price of about $250 per round trip. During this period, a total cargo movement in the order of 4 million lbs was carried at an average cost of 26¢ per lb.

8.7.3 Local Transportation

The following account of establishing the local overland transport at Deception Bay should be typical of many Arctic projects.

Forty miles of road from the Deception Bay wharf site and storage building to Asbestos Hill mine site was commenced and were started and built in their initial form in 1965/66. A later contract to rebuild portions of this road, raise and improve certain sections, required approximately 400,000 cu.yds. of fill during the 1970 and 1971 season. A new bridge on the Murray River was shipped in the 1970 sealift and erected in April 1971 from the ice. At that time of the year the river is almost dry, it was possible to assemble the bridge on the river bed and then lift it into position. Subsequently the old bridge was dismantled, shortened and modified to requirements and re-erected at Bombardier Creek. All this was completed prior to of the spring run-off, at the end of June, when the bridges were ready for traffic.

From the Deception Bay beach storage area, all materials were transported to Asbestos Hill (37 miles) or to the wharf site (3 miles). This local forwarding was handled as required to suit erection schedules, by 2 low-bed trailers and 2 high-boy trailers which could carry 20 or 30 tons and 1 unit up to 65 tons. In the final hauling stage at the end of 1971 pup trailers were also used from the future fibre-hauling equipment fleet to carry miscellaneous mechanical parts, at the same time Kenworth trucks were hauling fuel.

In total, approximately 9,000 short tons of material and equipment were transported to Asbestos Hill and 7,000 to Deception Bay wharf site. During the construction period 1,000,000 gallons of fuel were transported over this road system.

8.7.4 Support System

A permanent source of supply of potable water is often a major problem at arctic construction sites. There is little likelihood of groundwater because of the permafrost, so a surface source is mandatory.

Similarly, sewage disposal is a problem because of permafrost conditions where septic tank drain systems do not normally operate. Since streams are solidly frozen in the winter, disposal into the rivers is not practical even excluding environmental factors.

These problems were solved at Deception Bay as follows:

Water Supply System

Potable water was supplied to the plant site from a creek where a small dam was built to create a reservoir. A gasoline-engine-driven pump, with a plastic pipe line approximately 1 mile in length, supplied water to the storage tanks. This system was kept in operation during the moderate periods of the year; during the winter, water was pumped from a nearby lake into tank trucks and transferred by road to the plant site.

Water was stored in two un-insulated wood-stave tanks with a combined capacity of approximately 500,000 Imperial gallons. The water supply system was designed on the requirement of continuous recirculation and heating to prevent freezing. A heated and insulated pumphouse adjacent to the storage tanks was equipped with three electric and two diesel pumps, which provided service for water heat exchangers and controls for the continuous circulation system.

A loop piping system supplied water to the camp site and to the plant complex. The piping system is installed in permawalks for ease of maintenance and observation and to prevent disturbance of the permafrost.

The entire shore based facilities were provided with a fire protection system by means of hydrants and hose connections. The warehouse is equipped with a dry pipe sprinkler system and the mill area with a dry standpipe system. Water pressure is available at 100 psi for fire protection, which is reduced to about 40 psi for domestic consumption.

Sewerage System

Sewage is collected through a network of wood-stave pipes which were installed in permafrost, embedded in granular material below the active layer of the ground surface. Sewage is treated in a package-type, factory-built, complete mixing, extended aeration treatment plant (Smith and Loveless OXIGEST). The plant was installed at ground level, insulated and enclosed in a prefabricated wooden building which is heated to about 16°C and ventilated.

Provisions were made for greater flexibility and for proper organic loading at periods of low personnel by splitting the treatment tanks in two compartments, with the capability to operate either one or both. The compressed air supply system was designed so as to control the volume of air required for oxygenation depending on the organic loading of the plant. Incoming sewage flows through a comminutor and treated effluent is chlorinated before leaving the plant. The outfall sewer pipe is insulated and heat traced to prevent ice build-up. Treated sewage then flows by gravity through a natural gulley into an existing receiving body of water.

8.8 Cost Control

Any cost control monitoring system of an arctic project must recognize the unforgiving nature of arctic construction, both in terms of logistics and construction schedule. For instance, if the contractor failed to install a structure in the time-window allotted, construction most likely will have to be stretched into another construction season. In such an event, the project costs will escalate significantly. Effective cost control of arctic project must place great emphasis on achieving milestone objectives.

Whereas construction delays or unexpected increases in construction quantities in the south can generally be countered by an increase in labour and equipment, it generally is not possible to do this in the arctic, since this approach requires an increase in camp facilities and a long lead time to organize sea lift of additional equipment to make these adjustments.

Another major element in effective cost control is the installation of a completely reliable transport system to the site. The loss of a key shipment can increase the project costs dramatically, often much more than the original value of lost goods. Insurance may not cover for the full cost of replacement, since the lost material or equipment may have to be airlifted to meet time schedule constraints, or the critical time window may be missed and another construction season added to project.

8.9 Quality Control

Since arctic marine structures are commonly prefabricated in the south and transported to the north, all quality control measures should be applied at the fabrication shop in the south. Trial assemblies of the entire structure or parts of the structure should be carried out in the fabrication shop and any deficiencies or lack-of-fit should be corrected in the shops before shipping.

It is generally not feasible to correct deficiencies found after the structure has been delivered to the arctic site. Corrective measures are very costly at this time. If at all possible, all construction materials should be carefully inspected at the fabrication shop in the south to ensure that they meet all specifications, before fabrication is undertaken.

CHAPTER 9

EXISTING ARCTIC MARINE STRUCTURES

9. EXISTING ARCTIC MARINE STRUCTURES

This chapter identifies the majority of existing marine structures presently known. In addition to port facilities, oil/gas related structures which must resist similar Arctic environmental conditions experienced by port facilities have been included. These structures now have an established history with respect to design, construction and operations.

9.1 Wharf Structures

1. Deception Bay, Labrador
   Asbestos Corporation Wharf
   Steel Sheet Pile Cells
   Design by FENCO ENGINEERS INC.
   Construction by Foundation
   Operations Commenced: 1972

2. Strathcona Sound Marine Terminal, Baffin Island
   Transport Canada
   Steel Sheet Pile Cells
   Design by Carr and Donald & PWC
   Construction by Poole Construction
   Operations Commenced: 1976

3. Little Cornwallis Island
   Cominco
   Steel Sheet Pile Cells and Barge Plant
   Design by Bechtel
   Construction by Joint Venture including DB, Comstock and Tower
   Operations Commenced: 1981-82

4. Prudhoe Bay, Alaska
   Owner
   Two Wharf Structures
   Design by?
   Construction by?

5. Supply Wharf - Tuktoyaktuk
   Owner - Dome Petroleum
   Designed by Albery Pullerits Dickson & Associates
   Construction by Poole Construction Ltd. (PCL)?
   Operations Commenced: 1979

6. Wharves at Cooke Inlet
   Alaska Port Authority
   Design by Earl & Wright (three wharves)

Kelly, Petelco, Fritz and Forssen (one wharf)
Operations Commenced:

7. Wharf on North Slope - Canada
Piled Wharf (Failed)
Design by PWC
Construction by Poole Construction Ltd.
Operations Commenced: 1960's

8. Port of Churchill, Manitoba
Wharves - NHB
Design by PWC

9. Greenland Wharves
Thule, Black Angel Mine and Godthaab

10. Labrador Ports

(i) Place: Nain

Type of Construction: South section - untreated round timber cribwork with crib span approach plank deck.

North section - steel pipe piles with steel caps, untreated 2" x 8" laminated subdeck and 4" plank deck.

Design by: South section - PWC

North section - PWC

Contractor: South section - Glen Construction (no longer in business) - 1962

North section - Gid Sacrey Ltd. (St. John's) - 1974

(ii) Place: Davis Inlet

Type of Construction: Concrete filled steel pipe pile bents with concrete deck on outer portion. Approach is constructed of untreated round timber cribwork.

Design by: PWC

Contractor: Gid Sacrey Ltd. - 1983

(iii) Place: Hopedale

Type of Construction: Fully ballasted creosoted timber cribwork, span, and post construction. Plank deck.

Design by: PWC

Contractor: Twillingate Engineering - 1966 (firm now under new management)

(iv) Place: Postville

Type of Construction: Fully ballasted untreated round timber cribwork built over untreated round timber pile bents above elevation +2.5 feet. Plank deck.

Design by: PWC

Contractor: Pelly Enterprises Ltd. (Springdale) - 1971

(v) Place: Makkovik

Type of Construction: Untreated round timber cribwork approach with steel pipe pile bents. Steel caps, laminated subdeck, untreated plank deck.

Design by: PWC

Contractor: Avalon Construction (St. John's) - 1978

(vi) Place: Rigolet

Type of Construction: Untreated round timber cribwork with untreated round timber crib and span approach. Plank deck.

Design by: PWC

Contractor: Pelly Enterprises - 1977

(vii) Place: Goose Bay

Type of Construction: Main Dock - wooden pile bents with relieving platform deck.

West Dock - composite steel and wood side bents. Cane and asphalt deck.

Design by: Main Dock and West Dock - O.J. McCulloch

Contractor: Main Dock - unknown (1950)

West Dock - unknown (1959)

(viii) Place: Cartwright

Type of Construction: Fully ballasted cribwork.

Design by: USAF

Contractor: Unknown (1952)

(ix) Place: Black Tickle

Type of Construction: Untreated round timber cribwork. Plank deck.

Design by: PWC

Contractor: Gid Sacrey Ltd. - 1976

(x) Place: Port Hope Simpson

Type of Construction: Creosoted timber pile bents with composite timber concrete deck.

Design by: PWC

Contractor: Unknown - 1965

(xi) Place: Fox Harbour

Type of Construction: Untreated round timber cribwork and plank deck.

Design by: PWC

Contractor: Grant Engineering Ltd. (no longer in business) - 1979

(xii) Place: Red Bay

Type of Construction: a) creosoted timber cribwork over creosoted piles red block.

b) creosoted timber crib and span approach. Concrete deck.

Design by: PWC

Contractor: a) Gid Sacrey Ltd. - 1974

b) Pelly Enterprises Ltd. - 1977

11. Frobisher Bay - Baffin Island
    Wharf - PWC
    Designer PWC
    Current

12. Broughton Island Rock Wharf

13. Resolute Bay

14. Shore Protection at Tuktoyaktuk

9.2 Oil/Gas Related Marine Structures

1. Tanker Caisson - Beaufort Sea
   Dome Petroleum
   Design by Dome
   Construction by Japanese Contractor
   Operations Commenced: 1982-83

2. Tarsiut Island - Beaufort Sea
   Dome and Gulf Oil
   Concrete Caisson Island Structure
   Design by Swan Wooster
   Construction by Tower Arctic Ltd. & Dillingham/RIEDEL
   Operations Commenced: 1981

3. Steel Caisson Island - Beaufort Sea
   Esso
   Steel Caisson Structure
   Design by APD and Swan Wooster
   Construction by Japanese Shipyard
   Operations Commenced: 1983-84

4. Conical Island Platform - Beaufort Sea
   Gulf
   Conical Steel Ciasson Structure
   Design by Lavalin/Earl and Wright
   Construction by Japanese Shipyard
   Operations Commenced: 1983-84

5. Earth Island Structures (multiple) - Beaufort Sea
   Esso, Gulf
   Design by Esso
   Construction by Esso
   Operations Commenced: 1973

6. Movable Steel Caisson Structure
   Gulf
   Design by Swan Wooster
   Construction by Japanese Contractor
   Operations Commence: 1984

7. Drilling Platforms - Cooke Inlet Alaska
   Owners - Shell, Aramco and others
   Designs by Earl & Wright, Brown and Roote and others

8. Ice Structures
   Floating Ice Platforms and Roads
   Grounded Ice Platforms and Roads

9. McKinley Bay Dome

10. Lighthouse Structures

11. Norman Wells Development (6 islands)

CHAPTER 10

INFORMATION DEFICIENCIES AND RECOMMENDED RESEARCH AND DEVELOPMENT

10. INFORMATION DEFICIENCIES AND RECOMMENDED RESEARCH AND DEVELOPMENT

10.1 Marine Environment

Concerns to be addressed with regard to the collection of Marine Environmental Data have been listed in a report to the Department of Fisheries and Oceans by Lavalin Services Inc. Concerns, specifically related to the Canadian Arctic and a suggested list of research projects to overcome these, are as follows:

10.1.1 Structural Icing

Predictions of storms likely to cause severe icing, as well as their duration, is the responsibility of the weather service. Improved predictions will come from an improved weather service data collection system. The number of freezing days when a ship or rig is subject to freezing spray, is better predicted by having longer time spans of temperature data. Temperature readings are now currently the responsibility of the AES (Atmospheric Environment Service, Canada).

Research Projects

Strategies for coping with structure icing must be developed. The structures may be required to be designed for the following alternatives:

1. to take the appropriate design ice load
2. fitted with de-icing devices
3. fitted with icing build-up monitoring sensors

10.1.2 Currents

Because of the severe ice conditions that may be met in the Beaufort Sea, Arctic islands and Labrador Sea, current loading is not considered critical with regard to the in-place structure. However, for any structure that has to be floated and towed to an Arctic site, winds, waves or currents may have a critical effect during this phase.

Estimates of extreme waves occurring in the future will be made by the hindcasting of waves on the basis of meteorological data of the past. If direct measurements of waves are available in the area, wave statistics can form a solid basis for hindcasting.

Once a reasonable data base has been collected for a given area, it is possible to use statistical methods to calculate maximum wave height and frequency return periods. A data base already exists for some areas of the Beaufort Sea, Labrador Sea, Grand Banks, Scotian Shelf and the Pacific. However, most of the offshore data is related to drilling operations in the calmest period of the year. Data is collected now by the Marine Environment Data Service (MEDS), the Meteorological and Oceanographic Centre at Halifax, Sea Surface Marine Observations, and the Atmospheric Environment Service.

Research Projects

To overcome the above deficiencies, the following reasearch is suggested:

1. Over Horizon Radar - further development of over horizon radar would assist in operational requirements for wave prediction and also for ice and iceberg detection and management.

2. Real Time Current Measurement - there is a need to develop instrumentation to measure and transmit water velocities in the vicinity of floating production platforms. The need is greatest for surface or near surface velocity. The data will be utilized in station keeping environmental loading analysis, for ice and iceberg management.

3. On-going work on the improvement of equations for current forces.

10.2 Ice Technology

The following notes of recommended research and development are based largely on the report on Energy-Related Ocean Engineering Research and Development prepared by Lavalin Services Inc. for the Department of Fisheries and Oceans.

There still exists a need for much research into the nature and values of the mechanical properties of saline and non-saline ice in salt water. Considerable effort is required to gain practical knowledge of the thermal, acoustic and dielectric properties of such ice features.

In order to improve the quality, comparability and usefulness of the measurement and test data resulting from investigations, it is necessary to standardize sea ice and iceberg ice measurement techniques and testing methods for field and laboratory environment as follows:

Research Projects

1. Standardization of Ice Properties and Ice Features Measurement Techniques and Testing Methods for Field and Lab Environment

   The results of nominally similar measurements and tests vary greatly. Almost every ice research group uses different measurement and testing methods. This has proved a hindrance to the development of the ice engineering field. In order to improve the quality, comparability and usefulness of the measurement and test data resulting from investigations, it is necessary to standardize ice measurement techniques and testing methods for field and laboratory environment.

2. Ice Properties Program

Further research programs into the investigation of various types of ice features should be carried out to identify in particular the engineering properties of multi-year floes and pressure ridges as well as icebergs, ice islands and ice mounds. Research must also continue on first-, second-year and frazil ice and saline ice characteristics. Properties to be investigated include:

- Mechanical properties: compressive, tensile, shear and flexural strengths, multiaxial stress states and long-term loading, dynamic and static elastic modulii, and Poisson's ratio.
- Thermal properties: latent and specific heats, thermal conductivity and diffusivity and density.
- Dielectric properties: dielectric constants and loss, resistivity, emissivity.
- Acoustic properties.
- Friction and adhesion parameters.
- Accretion rates.
- In-situ surface roughness of the features.
- Salinity, temperature, grain structure (crystallography)

This knowledge, together with research into ice dynamics would lead to solutions of the problem of ice forces against structures.

CRREL has recently undertaken an extensive program into the mechanical properties of multi-year ridges and some strength testing has been carried out on icebergs.

3. Sea Ice Dynamics Model

The development of a near field and a far field forecasting model for sea ice movement is recommended.

The model should be able to predict sea ice movement and deformation, opening and closing of leads.

The research and development in the program should be oriented to an operational system. The model should also be able to regenerate the past history of the ice (hindcasting).

Different models will be needed for the Beaufort Sea, the Labrador Sea and Davis Strait where the oceanography and the sea ice conditions are very different.

Also, a regional sea ice generation and degeneration model should be developed and coupled with the forecasting model.

The sea ice movement operational program should be an end to end system. It should include: data collection, processing, interpretation and delivery of the ice forecast to the users in a proper format.

4. Satellite Program

In order to supply time series input to the forecasting model described in the previous project, a Canadian Satellite Program needs to be developed which includes an all-weather, year-round ice monitoring program. The proposed RADARSAT project, scheduled for operation in 1986, is expected to include such a program. This satellite should be of such a resolution to identify the following:

- Fast, pack and multi-year ice movement
- Floe size
- Ice concentration
- Ice type classification and distribution
- Pack ice boundaries
- Ship tracks.

The program should include data collection, processing and interpretation and the output formatting and transmission.

Research and development has proceeded towards computer interpretation techniques of satellite data spectrum as well as in the display techniques of the final output for the users and should be continued.

5. Sea Ice and Iceberg Remote Sensing Programs

The development of combined active/passive remote sensing sea ice algorithms should be continued.

Development of remote sensing packages for on-site field and aircraft experiments require real-time capability, availability of technical staff and expertise to repair and modify the system and supporting services on-site.

Development of ship-borne remote sensing systems for hazard detection is an ongoing industry priority and should continue within the mandate of Research and Development activities for the remote sensing community.

6. Arctic Ice Engineering and Cold Regions Laboratory

Rather than create a new ice research centre, efforts should be put to coordinate the activities of the existing ice engineering and cold region research laboratory (industry, consultants, institution and university), in order to insure a reasonable level of ice engineering and cold regions research.

A Field Laboratory located in the west part of the Archipelago, where multi-year ice and first-year ice are easily accessible, should be created.

This establishment should operate year round and perform insitu and laboratory ice testing, as well as ice monitoring.

7. Iceberg Dynamics Program

An operational far field and near field iceberg dynamics forecasting model should be developed and computerized.

The model should consider the following:

- Prediction of drift paths and relationships to surrounding open water and ice.
- Iceberg stabilities: iceberg rotation algorithm.
- Prediction of periods and areas of high iceberg concentration.
- Ablation, calving and decay processes.

The model should be operation oriented and it should be able to do hindcasting.

8. Iceberg Reconnaissance Program

Icebergs cannot be detected properly by satellite due to the inadequate satellite resolution. Regional iceberg detection by airborne SAR/ALAR and/or passive microwave imagery should be a priority research and development activity.

9. Iceberg Scour Program

Research and development programs of iceberg scour and iceberg management are industry priority concerns and should be continued.

10.3 Geotechnical Research Topics in Submarine Permafrost

The following are some topics for research which could provide a better understanding and allow better design in submerged marine permafrost:

1. Laboratory and Theoretical

   A. Studies into the influence of salt on permafrost, e.g. salt profile, migration, chemical and physical soil properties.

   B. Conduct a literature review of methods to install a large diameter steel pile (pier) which could resist large lateral loads. Develop a feasible program for a field trial.

2. Field Studies

   A. Development of geophysical logging to obtain quickly, information on ice distribution, density, salinity, soil type, etc. in a borehole, thereby decreasing the amount of required sampling which is time consuming and therefore costly.

   B. In-situ pressuremeter testing of submarine permafrost to obtain strength deformation and creep parameters. In-situ testing will be very valuable because it is difficult to secure and maintain submerged permafrost samples in the in-situ state due to the "warm" nature of submarine permafrost.

   C. Measure typical land/marine permafrost thermal profiles which would be of great asset in future designs of submarine pipelines for land facilities and near shore structures.

   D. Measure dynamic properties of major classes of submarine permafrost to obtain typical seismic design parameters.

3. Construction Field Tests

A. Field trial of driving sheet piles in submarine permafrost to evaluate most effective type of hammer and required sheet pile section to withstand difficult driving condition.

B. Install thermosyphons around a steel tube pile to increase the permafrost area and decrease the temperature which will increase the lateral load capacity of the pile from frozen soil considerations. Conduct a lateral test load on the pile.

10.4 Responses to the Ice Environment

10.4.1 Sea Ice Forces

Research programs concerned with various failure modes have developed force to failure type models for various offshore structures. Results of the models seem to agree with the few accessible, measured values.

Considerable research effort has been centred on determining ice forces on structures. Ultimate forces on structures located in ice waters are almost entirely due to the action of ice. The amount of easily applicable experimental data is still small and purely analytical approaches are complex and not fully developed. The need for economically sound offshore structures has prompted industry to evolve many ice failure models. To develop better integrated models than those in existence requires a better understanding of the ice itself. Design work uses empirical or historical estimates of forces, but the mechanical properties of ice are so complex and variable that analytical estimates must be well supported by experiments.

Full scale experients are expensive and must consider the magnitude and direction of ice loads, the nature of the ice, mechanical properties, ice structure contact area, shape of structure, direction of ice movements, and the oscillating nature of the ice loads.

Conventional reduced scale models involve distortions of scalar relationships or the substitution of other materials to represent the ice. The interpretation of results is then ambiguous without full scale verifications.

Recent work indicates that centrifuge model testing facilities can be used with scaled down dimensions and yet maintain the natural ice properties.

Research Projects

With respect to Sea Ice Forces, the following research programs are identified:

1. A Mathematical Algorithm of Ice Pressures on a Structure at the Ice-Structure Boundary

Theoretical considerations of single ice failure modes, without disturbance from variations in associated parameters, have been studied with great care and modelled. A detailed knowledge of effects important to the ice pressure problem has been reached in that way. However, there is a lack of models which can integrate the individual failure modes and provide the magnitude of ice pressure occurring in nature when conditions are more mixed.

Therefore a mathematical model of the ice pressures on a structure at the ice-structure boundary should be developed and computerized for the three following cases:

a) Ice attached to the structure (Frozen)
b) Ice molded around the structure (Plastic flow)
c) Ice collision with the structure (Impact)

2. Direct Measurements of Time Sequence of Ice Loads on a Full Scale Structure

The advantage of using a model is primarily that time series of ice pressures on the structure can be generated by hind casting where the input variables are available. However, even for this case it is beneficial to add direct measurements of ice pressures on the structure to verify and calibrate the proposed model.

Therefore, field measurements of time sequence of ice loads on a full-scale structure have been carried out on Beaufort Sea platforms, on Hans Island in the High Arctic and on several wharves in the sub-arctic.

More such field measurements are recommended which would take into account all the parameters that at present are thought to play a role in the entire problem of ice pressure on a structure, or at least a set of parameters that constitute an independent part of the problem.

During this program, ice behaviour at the ice structure boundary should be systematically observed, in order to correlate the failure modes of the ice to the measured pressure.

The program should also include the measurement, at the site area, of mechanical and thermal properties of the ice and the meteorological and oceanographic parametes influencing the ice pressures.

10.5 Existing Regulations and Guidelines

10.5.1 Environmental Policy

Currently the possibility of environmental disturbance in the Arctic and its ecology is generally veiled by "unique", "fragile", "impact upon indigenous people", etc.

Studies on these issues are needed resulting in a comprehensive environmental regulation which could preferably be placed under one jurisdictional authority for administration and enforcement.

10.5.2 Labour Codes

The governing labour codes in the Canadian Arctic are provincial, federal and the labour codes of the Northwest Territories.

As construction projects increase in the Canadian Arctic, it would be advantageous to consolidate these into one code to be administered by a single authority.

On-going research progams to refine safety limits should be the responsibility of this authority.

10.6 Design and Construction

Research projects as proposed in the above sections (10.1 to 10.4) would also benefit the design and construction of structures in the Arctic. More specifically, on the basis of literature search conducted during the preparation of this Handbook, the following have been identified:

- Studies to determine the effects of bottom contact and resistance on ice wasting around a structure in shallow waters.
- Berm construction techniques to decrease cost and to minimize maintenance, by one, or a combination of:
  - slope strengthening
  - slope stabilizing
  - slope protection
  - erosion protection methods.
- Construction equipment and methods for:
  - soil placement methods
  - large volume hauling capacity.

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Volume 2

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17. Abstract

This reference document, in two volumes, provides a compendium of information and current practice in the design and construction of Arctic marine structures. It presents information on the Canadian Arctic related to economic resources, environmental, ice and geotechnical conditions and provides essential technical information upon which design criteria for wind, waves, currents, snow loads, ice forces and geotechnical conditions are based. It discusses existing engineering guidelines, regulations, standards and various options for the design and construction of ice resistant structures and identifies information deficiencies in these areas and indicates where research and development is required. A selective, annotated bibliography, sources and titles of pertinent technical publications and a list of agencies and organizations providing information on the Arctic, are also provided.

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Cet ouvrage en deux tomes constitue un recueil théorique et pratique des méthodes de conception et de construction de structures maritimes dans l'Arctique. Il renseigne sur la région arctique du Canada: ressources, économie, conditions environnementales, glacielles et géotechniques et présente les données techniques de base ayant servi à l'élaboration des critères de calcul relatifs aux forces exercées par le vent, la houle, les courants, les glaces, la neige et aux conditions géotechniques. Il traite de la réglementation, des guides et des normes en vigueur concernant la conception et la construction de structures à l'épreuve des glaces; souligne les lacunes constatées dans les divers domaines abordés et met en évidence les secteurs où des travaux de recherches et développement sont nécessaires. Il comporte une bibliographie annotée d'ouvrages sélectionnés, donne le titre et la maison d'édition des diverses publications intéressant le domaine considéré et dresse la liste des sociétés et organismes susceptibles de renseigner les intéressés sur tout ce qui touche à l'Arctique.

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TABLE OF CONTENTS

SUBJECT — Page No.

1.0 Ice Technology
- 1.1 Type, Structure and Morphological Properties 1-57
- 1.2 Ice Structure Interaction 58-146
- 1.3 Ice Structure Interaction, Moving Vessels 147-156
- 1.4 Ice Scour 157-169

2.0 Arctic Geotechnique 170-221

3.0 Responses to the Ice Environment
- 3.1 Utilizing Ice 222-240
- 3.2 Ice-Resistant Schemes 241-247
- 3.3 Ice Control 248-252

4.0 Existing Regulations and Guidelines 253-264

5.0 Design Guidelines 265-307

6.0 Construction Procedures and Techniques 308-323

7.0 Case Histories 324-325

8.0 Instrumentation and Monitoring 326-330

APPENDICES

Sources of Information on the Arctic

APPENDIX 1 - List of Agencies and Organization 331-335

APPENDIX 2 - List of Useful References 336-353

APPENDIX 3 - List of Conferences 354

APPENXIX 4 - List of Companies Providing Sealift Transportation in the Canadian Arctic 355-359

1.0 ICE TECHNOLOGY

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Parameters on Fracture Strength of Sea Ice	Urabe, N. Yoshitake, A. Iwasaki, T. Kawahara, M.	Trans ASME, J. Energy Resour. Technol., 105 (1983)1, March.	1983	53
The Flexural Failure of Hummock Fields and Large Floes at the Summer Ice Edge in the Beaufort Sea	Wadhams, P.	Sponsor: Dome Petroleum Limited	1981	54
Crystallographic Studies and Strength Tests of Field Ice in the Alaskan Beaufort Sea	Wang, Y. S.	Ocean Engineering under Arctic Conditions, at the Norwegian Institute of Technology, August 13-18, 1979, proceedings, v.1	1979	55
Sea Ice Properties and Geometry	Weeks, W.F.	AIDJEX Bulletin, No. 34	1976	56
The Growth, Structure, and Properties of Sea Ice	Weeks, W. F. Ackley, S. F.	U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire	1982	57

SOURCE

Bates, H.F.; Shapiro, L.H.
"Plane Waves in a Viscoelastic Floating Ice Sheet"
(Journal of Geophysical Research, v. 86, no. C5)
May 20, 1981

SUMMARY

The correspondence principle of viscoelasticity is applied to obtain the plane-wave impulse response of a laterally compressed viscoelastic plate floating on a perfect liquid. The system is analyzed as a wave guide having a small damping factor. A four-parameter linear viscoelastic model is used to simulate the characteristics of a sheet of floating ice. Values appropriate for small deflections in sea ice are used to produce illustrative examples of the displacement and the vertical loading stress caused by the bending produced in an ice sheet by plane waves arising from a unit line force moving uniformly across the sheet. Because the displacement of the viscoelastic plate remains finite, this technique provides a means for making engineering estimates of the stress produced by waves at the critical frequency.

KEY WORD	CLASSIFICATION
Ice Technology	Viscoelastic Floating Ice Sheet

SOURCE

Bogorodskii, V.V.; Gavrilo, V.P.; Gusev, A.V.; Nikitin, V.A.
"Deformation characteristics of Sea Ice"
Hanover, New Hampshire: Cold Regions Research and Engineering Laboratory,
1981
Draft Translation - U.S. Army CREEL, 750
Doklady - Akademiia nauk SSSR, V.252, no. 5, 1980

SUMMARY

The authors used a "pressiometric technique" to study the deformation characteristics of ice directly in the ice cover. A probe, comprised of a rubber-coated metal cylinder, is a part of the pressiometric complex which is inserted in the ice cover. ...The accuracy of the ice deformation measurements is within 0.001 mm. The results of the calculations given in this paper are graphically depicted.

KEY WORD	CLASSIFICATION
Ice Technology	Deformation Characteristics of Sea Ice

SOURCE

Colony, R.
"Daily Rate of Strain of the AIDJEX Manned Triangle"
AIDJEX Bulletin No. 39, May 1978

SUMMARY

The daily changes in position of three manned camps during the AIDJEX experiment have been used to estimate the large-scale strain rate of sea ice. A definition of mean strain for a large area of sea ice is proposed. Estimates of the daily rate of mean strain are given in tabular form. ...A spectral analysis of the time series of stretching rate provides evidence that the daily rate of strain is a good measure of the instantaneous strain rate.

KEY WORD	CLASSIFICATION
Ice Technology	Strain Rate of the Aidjex Manned Triangle

SOURCE

Croasdale, K. R.
"The Nutcracker Ice Strength Tester and Its Operation in the Beaufort Sea"
Proceedings - IAHR Symposium: Ice and its Action on Hydrualic Structures, 1st, Reykjavik, Iceland, 7-10 Sept., 1970
APOA Project No. 1: Nutcracker Ice Strength Tests, 1969-70
Report No. 2

SUMMARY

Growing energy consumption and dwindling reserves in the populated regions is spurring the search for oil in the frontier areas of the far North. This paper describes the work sponsored by several Canadian oil companies aimed at providing ice strength data for the operation of a novel ice testing device is described. Some of the results obtained during tests in January and February of 1970 are presented and discussed.

KEY WORD	CLASSIFICATION
Ice Technology	Nutcracker Ice Strength Tester

SOURCE

Fenco Consultants Limited
"Beaufort Sea Summer Ice Testing Project"
Calgary, Distributed by APOA, 1973
APOA Project No. 60: Beaufort Sea Summer
 Ice Testing Project

SUMMARY

To study the summer ice properties and the physical parameters of the floe such as surface area, shape, thickness, specific gravity, salinity, temperature and drift velocity of the ice floes. One set of measurements was carried out closely after breakup by July 15 to July 22 and a second set in the open water season from September 18 to September 21. Triangular plate tests, circular plate tests and borehole jack tests were the insitu tests used to obtain strength parameters.

KEY WORD	**CLASSIFICATION**
Ice Technology	Beaufort Sea Testing Project

SOURCE

Frederking, R. M. W.; Timco, G. W.
"Mid-Winter Mechanical Properties of Ice in the Southern Beaufort Sea"
Ottawa: National Research Council of Canada, Geotechnical Section, Division of Building Research, Hydraulics Laboratory, National Research Council of Canada, Division of Mechanical Engineering

SUMMARY

Ice property measurements were carried out during ice breaking trials of the "CANMAR KIGORIAK" during the winter of 1979-80, primarily in landfast ice in the Southern Beaufort Sea in the vicinity of McKinley Bay. They included crystallographic analysis to establish ice type and structure, temperature and salinity profiles, and uniaxial compression and "Brazil" strength tests. The work was performed on board ship at the time of the trials.

The ice under study included samples of first-year ice covers and multi-year pressure ridges. Sampling and measurement techniques are described. The strength results are discussed in terms of salinity, loading rate, grain structure, sample orientation and position in the ice cover. Strength results were found to agree generally with values in the literature.

KEY WORD	CLASSIFICATION
Ice Technology	Mechanical Properties of Ice

SOURCE

Frederking, R. M. W.; Timco, G. W.
"Uniaxial Compressive Strength and Deformation of Beaufort Sea Ice"
Ottawa: National Research Council of Canada, Division of Building Research
1967

SUMMARY

Strength and deformation behaviour of horizontally oriented specimens of granular and columnar-grained ice were measured in the field. Cylindrical specimens were loaded on compliant platens and prismoidal specimens on steel platens to provide a range of loading system stiffness. Loading system stiffness proved to have a significant effect on strength when the results were interpreted in terms of nominal strain rate, but in terms of stress rate it was largely eliminated. The strength of the granular ice (2.5 - 4 MPa) was substantially higher than that of columnar-grained ice (1 - 2.5 MPa). Regardless of grain structure, the specimens all failed by yielding at a strain of about 3×10^{-3}.

KEY WORD	CLASSIFICATION
Ice Technology	Uniaxial Compressive Strength and Deformation of Ice

SOURCE

Gladwell, R.W.
"Field Studies of Eight First-Year Sea-Ice Pressure Ridges in the
Southern Beaufort Sea"
Imperial Oil Limited.
Calgary: Distributed by APOA, 1976
APOA Project No. 75: Field Study of First-Year Ice Pressure
Ridges

SUMMARY

...The project objectives were: 1. To measure the shape and physical properties of several first-year pressure ridges, both grounded and floating, in various water depths out to the annual pack ice of the Southern Beaufort Sea. This data will provide input to structural design criteria and logistics planning for oil industry activity in the area. 2. To establish a ratio of ridge keel depth to soil height necessary for the evaluation of total ridge size from aerial photographs. Data presented include cross-section drawings of the ridges; temperature, salinity, density and brine volume profiles of the constituent ice; results of Menard Pressuremeter strength tests; sea water salinities; analysis of sea bottom soil samples; and a report on ridge profiling using the Geophysical Survey Systems electromagnetic subsurface profiling techniques ...

KEY WORD	CLASSIFICATION
Ice Technology	Sea-Ice Pressure Ridges Studies

SOURCE

Gold, L. W.
"Young's Modulus of Ice and Ice Engineering Problems"
Ottawa: National Research Council of Canada

SUMMARY

Traetteberg et al have recently completed an investigation of the time and temperature dependence of Young's modulus for two types of ice. The analysis of these results indicated that the visco-elastic behaviour of ice is not simple. Evidence was found for two relaxation processes, one with a relaxation time that increased with the time of application of the load raised to the power of 2/3. The latter relaxation process appeared to dominate the time dependence of Young's modulus for time greater than 0.1 s. A relationship for the time dependence of Young's modulus, consistent with the observations over the time range of 0.1 to 10^2s, was derived.

For the conditions of the measurements, this period of time corresponds to the range in strain rate associated with the ductile to brittle transition in ice, and range in time of interest for ice pressure and bearing capacity calculations. The significance of this time dependence of Young's modulus is discussed with respect to the ductile to brittle transition, change in characteristics of the failure behaviour associated with the transition, and aspects of the ice pressure and bearing capacity problems.

KEY WORD	CLASSIFICATION
Ice Technology	Modulus of Ice

SOURCE

Hausler, F. U.
"Druckfestigkeitsversuch mit Salzwasser-Eis = Compression Strength Tests on Saline Ice"
Intermaritec-80, Conference Report/International Conference on Marine Sciences and Ocean Engineering, Hamburg, Germany, 1980
Edited by C. Kruppa and G. Clauss. Hamburg: Hamburge Messe and Congress GmbH, 1980

SUMMARY

...The investigation of the mechanical properties of sea-ice uniaxial compression strength tests on saline ice were performed at the ice laboratory of the Hamburg Model Basin. ...for the first time in ice research brush-type loading platens were used ... which provide a very small transverse strain restriction. The tests were performed on a closed-loop testing machine which allows the strain rate to be controlled. The strain transducers were directly fixed to the cubic ice probes. In this way the disturbing influences of the loading frame's stiffness could be eliminated. The results show the effects of strain rate and specimen temperature on compression strength and stress-strain-behaviour of saline ice, which was frozen under simulated natural conditions out of a natrium-chloride solution of 30 per mill salinity.

KEY WORD	CLASSIFICATION
Ice Technology	Compression Strength Tests on Saline Ice

SOURCE

Hausler, F. U.
"Comparison Between Different Yield Functions for Saline Ice"
Proceedings of the Second Symposium on Applied Glaciology
held in New Hampshire, USA, 23-27 August, 1982
Annals of glaciology, v. 4, 1983

SUMMARY

Data obtained from tests of uniaxial and multiaxial compressive strength on saline ice have been used to determine the coefficients of the Smith yield function, which uses seven parameters, and of the Pariseau yield function, which uses five. Both functions describe orthotropic materials and have been reduced for transverse isotropy. ... The values for tensile strength have been obtained from data published by other researchers. The ice-strength values computed by means of the two yield functions were compared with measured ice strengths; the seven-parameter Smith yield function provides reliabile results over the whole stress space, while the similar Pariseau yield function is only applicable within a restricted area of the stress space.

KEY WORD	CLASSIFICATION
Ice Technology	Yield Functions for Saline Ice

SOURCE

Hibler, W. D.
"Modeling Pressure Ridge Buildup on the Geophysical Scale"
1980
Preprint of a paper to be published in the proceedings of the NRC
Workshop on Sea Ice Ridging and Pile Up, Calgary, October, 1980

SUMMARY

In large scale sea ice models ridging is modeled by redistributing thin ice into thicker categories. The way in which this redistribution is carried out can significantly affect the geophysical stresses in pack ice. This paper compares ice strength characteristics of several different redistributors and discusses the relationship of these redistributors with observed ridge morphological data. In addition, simulated Arctic Basin ridge buildup results using one of these redistributors are presented and compared to roughness observations reported in the literature.

KEY WORD	CLASSIFICATION
Ice Technology	Modeling Pressure Ridge Buildup

SOURCE

Ivchenko, V.O.; Kheisin, D.E.
"Determination of Internal Stresses in the Ice Cover Generated during Ice Drift"
Papers - Symposium on Thermodynamic Interactions Between the Atmosphere and the Ocean in the Arctic, Leningrad, Sept. 25-30, 1972. Problems of the Arctic and the Antarctic, v. 43-44, 1974
Translation of: Oppedelenie vnutrennikh napriazhenii v ledianom pokrove, voznikaiushchika ppi dreife l'da.

SUMMARY

The ice cover can be regarded as an assemblage of mechanical objects, ...Thus analytical study of free waves of ice compression ... made possible quantitative determination of the influence of internal stresses in the ice cover on drift. The calculated zones of compression and their dynamics should be of definite practical interest.

KEY WORD	CLASSIFICATION
Ice Technology	Internal Stresses in the Ice Cover

SOURCE

Kennedy, J. B.; Iyengar, K. J.
"Rigid-Plastic Analysis of Floating Ice Sheets under Impact Loads"
Canadian Journal of Civil Engineering, v. 8, no. 4, 1981

SUMMARY

The deformation response of floating ice sheets under high intensity, short duration loads is examined. Using a rigid-plastic theory, together with a Tresca wield criterion, expressions are derived for the total time of response and the final deformed configuration of floating ice sheets. The influence of the magnitude of the impact load and the load-contact radius on the various design quantities such as deflection profile and stress distribution is discussed. Based on the results derived, a design method is presented to find the safe thickness of a floating ice sheet to sustain a given impact load. The method is illustrated with a numerical example.

KEY WORD	CLASSIFICATION
Ice Technology	Rigid-Plastic Analysis of Floating ice Sheets

SOURCE

Kivisild, H. R.; Iyer, S. H.
"Mathematical and Physical Modelling of Ice"
Proceedings - IAHR Symposium on Ice Problems, 5th, Lulea, Sweden,
7-9 August, 1978. Lulea, Sweden, International Association of
Hydraulic Research, 1978

SUMMARY

... The paper discusses the concepts of mathematical and physical modelling of ice, the rheological properties, the scaling problems, and materials used for modelling ice. The feasibility of using real ice and ways of overcoming distortions in similitude are discussed in detail.

KEY WORD	CLASSIFICATION
Ice Technology	Mathematical and Physical Modelling of Ice

SOURCE

Kohnen, H.
"Glaciological Research Relevant to the Construction of Ice-Going Ships"
Ocean Engineering, Vol. 3
1976

SUMMARY

The transportation of rich mineral resources from the Arctic by means of large ice-going bulk and oil carrier, is expected to be a suitable and economical technique. The construction of such large vessels requires the knowledge of various glaciological parameters of the sea ice and their dependence on Arctic environmental conditions, of particular interest on the small scale are the strength, elasticity, and metal to ice friction characteristics, on a larger geophysical scale relevant parameters are the ice stress, pressure, and movement rates and the relation of these parameters to the temperature and salinity of the ice and to the wind field and the ocean current. Furthermore electrical and electromagnetical properties of the ice are relevant to the navigation in ice covered waters by the aid of remote sensing techniques. The German shipyard A.G. Weser in Breman initiated in 1972 an expedition to the Canadian Arctic to study all relevant physical properties at one location and at the same time to comprehend the whole glaciological regime. The expedition was a cooperative effort between Brock University, St. Catharines (Canada) and the University of Munster (W. Germay). The field measurements were carried out in May and June 1972 on the sea ice between Pond Inlet (Northern Baffin Island) and Bylot Island, N.W.T. This article summarizes the essential results and presents a synthesis of all the results.

KEY WORD	CLASSIFICATION
Ice Technology	Glaciological Research

SOURCE

Kovacs, A,; Mellor, M.
"Sea Ice Pressure Ridges and Ice Islands"
Calgary, Distributed by APOA, 1971
Beaufort Sea Pressure Ridge and Ice Island Scouring
 Report No. 1
Technical Note - CREARE, Inc., No. 122

SUMMARY

The environmental conditions of ice-covered polar seas are described, with special emphasis on the pressure ridges and ice islands encountered in Mackenzie Bay and the Beaufort Sea. Techniques for determining the geometric configurations and the physical and mechanical properties of sea ice structures and ice islands are described. Profiles of pressure ridges were determined by surface surveys, drill hole probes, and side-looking sonar scanning; results are given for several multi-year ridges and one first-year ridge. Supplementary information obtained from dives under the ice is also given. Corresponding data are given for ice islands, with particular attention being given to contact between the ice and the sea bed. Measurements of temperature, salinity, tensile strength and compressive strength are given for ice taken from old pressure ridges, and factors influencing the interpretation of test data are discussed. The main report closes with a brief discussion of some of the findings. The appendices give complete diving reports, and a full report on the performance of the SR.N6 Hovercraft.

KEY WORD	CLASSIFICATION
Ice Technology	Sea Ice Pressure Ridges

SOURCE

Kovacs, A.; Morey, R. M.
"Investigations of Sea Ice Anisotropy, Electomagnetic Properties,
Strength, and Under-Ice Current Orientation"
Hanover, New Hampshire; Cold Regions Research and Engineering
Laboratory, 1980
CRREL report, 80-20

SUMMARY

...The fundamental relation between the average bulk brine volume of sea ice and its electrical and strength properties is discussed found that 1) average effective bulk dielectric constant is dependent upon the average bulk brine volume of the sea ice; 2) sea ice anisotropy, arising from a bottom structure of crystal platelets with a preferred o-axis horizontal alignment, can be detected by radio echo sounding measurements made not only on the ice surface but also from an airborne platform; 3) the effective coefficient of reflection from the sea ice bottom decreases with increasing average effective bulk dielectric constant of the ice, decreases with increasing bulk brine volume, and is typically one to two orders of magnitude lower than the coefficient of reflection from the ice surface; and 4) the losses in sea ice increase with increasing average bulk brine volume.

KEY WORD	CLASSIFICATION
Ice Technology	Investigations of Sea Ice Anisotropy

SOURCE

Kovacs, A.; Weeks, W. F.; Ackley, S.; Hibler, W. D., III
"Structure of a Multi-Year Pressure Ridge"
U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H.
(AIDJEX 1971)

SUMMARY

Three transverse profiles across a large pressure ridge located in the Beaufort Sea are presented. The ridge sail extended 4 m above sea level and the ridge keel 13 m below. The cross-sections of the ridge keel can be described as roughly semi-circular. This suggests that form drag coefficients for flow transverse to the long axes of multi-year ridges may be high (1.0). The ice comprising the ridge is extremely massive. All the inter-block voids that initially existed in the ridge at the time of its formation have been completely filled with ice. Examination of several salinity, temperature and brine volume profiles shows that much of the ice in the ridge has a very low salinity and is quite strong. These observations, coupled with icebreaking experience indicate that multi-year ridges are, indeed, significant obstacles to even the larges icebreaking ship and should be avoided if possible.

A very large first year ridge with a sail height of 12.8 m is also described. To the best of our knowledge, this is the largest free floating ridge yet recorded.

KEY WORD	CLASSIFICATION
Ice Technology	Multi-Year Pressure Ridge

SOURCE

Lane, J. F.
"On the Strengths of Sea Ice and a Correlation Between the Various Strength Tests"
Ottawa: National Research Council Canada, Division of Mechanical Engineering, 1979
Report - Canada. National Research Council, Division of Mechanical Engineering. Low Temperature Laboratory, LTR-LT-104

SUMMARY

A number of tests have been devised for measuring the physical strength characteristics of sea ice. Each test gives a different strength value even though the test may be measuring the same characteristic. Some method of correlating the various tests for comparison purposes is desirable.

KEY WORD	CLASSIFICATION
Ice Technology	Strengths of Sea Ice

SOURCE

Lepparanta, M.
"On the Structure and Mechanics of Pack Ice in the Bothnian Bay"
Helsinki: Merentutkimuslaitos, 1981
Finnish Marine Research No. 248

SUMMARY

Theoretical and empirical studies are made for the March-April period when thermal changes of ice mass are small. The ice pack in the research basin is fractured into separate floes the diameters of which are, considering the relative a real coverage, fairly evenly distributed from tens of meters to 4-5 km. The thickness of level is 1/2 m and the amount of deformed ice is comparable. Rates of deformation of pack ice are 0.0000001/s and their temporal scale surface shear stresses of wind and water on ice and the internal friction within the ice. Estimates of the bulk and shear viscosities of pack ice vary in the range 10,000,000 to 10,000,000.000 kg/g, while the compactness is 0.89-0.95. Largest viscosities result when the compactness is at its highest and at the same time either deformation rates are small or ice is ridging. Dissipation of kinetic energy in internal deformation processes is significant, and the main energy sinks are the friction in shearing ridges; the former is several times larger than the latter.

KEY WORD	CLASSIFICATION
Ice Technology	Structure and Mechanics of Pack Ice

SOURCE

Lewis, J. W.
"Recent Developments in Physical Ice Modelling"
Offshore Technology Conference, Houston, Texas
May 3-6, 1982

SUMMARY

The use of sodium chloride and carbamide doped ice for simulating real sea ice is reviewed. These ice modelling substances are shown to have certain limitations particularly with regard to scaling elastic modulus and crushing strength properties of sea ice. Other limitations regarding temperature sensitivity, need for cold rooms, and short time available for conduct of experiments, are discussed.

A synthetic model ice is described and its ability to simulate real sea ice is discussed. Comparisons are made with sodium chloride and carbamide doped model ice. The synthetic model ice is shown to more closely simulate real sea ice properties at small scale ratios than sodium chloride or carbamide doped ice. Other advantages of the material in regard to temperature insensitivity, removal of need for cold rooms and increased time for conduct of experiments are discussed.

Two full-scale/synthetic ice model-scale data sets are presented and used to discuss correlation between full-scale data and model-scale data collected in the synthetic ice.

KEY WORD	CLASSIFICATION
Ice Technology	Physical Ice Modelling

SOURCE

Lichtenberger, G. J.; Stegall, R. D.; Braun, C.; Zadow, D. W.; Sun Oil Company Limited
"Vertical Load Bearing Capacity Tests of Natural Ice, and of Artificial-Natural Ice Laminates: Resolute Bay, Winter 1974/75"
Calgary: Distributed by APOA, 1976
APOA Project No. 81: Ice Mechanics 1974-75, Arctic Field Test Program, Resolute Bay, North West Territories
Report No. 3-11
Original Publisher: Sunoco Science and Technology

SUMMARY

... The ice sheet was loaded with 20-foot and 30-foot diameter bolted steel tanks which were filled with sea water to the desired level or until breakthrough occurred. At each test site ice thickness and temperature profile were measured as well as the induced load deflections, inclinations, stresses and strains. The collapsed load data were correlated using Westergaards extreme fibre stress equation to yield an average rupture modulus of 242 psi for 30% to 55% artificial ice, built up by flooding and freezing upon a natural ice base. The rupture modulus of natural ice was found to be 248 psi. Ice deflection and inclination measurements showed a strong viscous contribution to the deformation. The data, descriptions and discussions of these tests are contained within this report.

KEY WORD	CLASSIFICATION
Ice Technology	Vertical Load Bearing Capacity Tests

SOURCE

Maser, K. R.
"An Analysis of the Small-Scale Strength Testing of Ice"
Physics and Mechanics of Ice, IUTAM Sump. Copenhagen, 1979, Springer-Verlag
1980

SUMMARY

The inadequacy of small-scale strength test results for the prediction of ice sheet strength is recognized. Certain patterns appear in these test results which suggest that the plasticity of the individual crystal is a controlling factor. It is found from previous investigations that ice crystal plasticity is dominated by basal glide, and that the stress-strain-time properties have the characteristics of strain softening. A stress-strain-time relation is proposed which best matches the reported results. This relation is used in analytical models which treat the small-scale sample as an assembly of grains. A modeling by springs and dashpots shows how failure stress in uniaxial tension increases with increasing strain rate in a given range. A finite element model for a polycrystalline sample gives quantitative support for this result, and the resulting curve is very similar to that obtained by previous experiments. The model also reveals the character of the nonuniform stress field associated with the coarse grained sample. Several directions for future research are discussed.

KEY WORD	CLASSIFICATION
Ice Technology	Small Scale Strength Testing of Ice

SOURCE

Morgenstern, N. R.; Nuttall, J. B.
"The Interpretation of Ice Strength from In-Situ Indentation Tests"
Calgary: Distributed by APOA, 1971
APOA Project No. 16: Theoretical Analysis of Ice Failure
Report No. 1

SUMMARY

Imperial Oil Ltd. and APOA have requested the writers to theoretical analysis of both data from ice pressures on bridge piers and from "Nutcracker" tests, with the aim of investigating the relationship between known mechanical properties of ice and the behaviour observed in these small prototype studies, and 2. if found warranted as the theoretical analysis progresses, a special review of existing experimetal data on the strength of ice in the context of the problem, with a view to making reommendations for testing in order to obtain appropriate data if it does not exist. ...This report presents the results of the theoretical study of the "Nutcracker" test and related test configurations. ...The report ends with conclusions regarding the use and limitations of the results presented here together with recommendations for more field and laboratory testing which will explore further the applicability of these results.

KEY WORD	CLASSIFICATION
Ice Technology	Ice Structure Interpretation From In-situ Tests

SOURCE

Murat, J.R.
"Essais en Flexion de Plaques de Glace de Mer" (Studies on the Flexibility of Sea Ice Sheets)
Montreal: Ecole Polytechnique de Montreal, 1978
Study supported by Polar Gas

SUMMARY

A report on tests conducted to test the strength and elasticity of sea ice.

KEY WORD	CLASSIFICATION
Ice Technology	Flexibility of Sea Ice Sheets

SOURCE

Nevel, D. E.
"Bending and Buckling of a Wedge on an Elastic Foundation"
Physics and Mechanics of Ice, papers
International Union of Theoretical and Applied Mechanics
Symposium, Technical University of Denmark, Copenhagen,
August 6-10, 1979. Edited by Per Tryde. New York, Springer-
Verlas, 1980

SUMMARY

When an ice sheet begins to slide up a sloping structure, the ice cracks radially from the structure creating wedges. Beam theory is used to analyze these wedges under the influence of both horizontal and vertical forces. Buckling and bending of these wedges are considered.

KEY WORD	CLASSIFICATION
Ice Technology	Physics and Mechanics of Ice

SOURCE

Nohguchi, Y.; Tabata, T.
"Effect of Sample Length on Uniaxial Compressive Strength of Sea Ice"
Low Temperature Science. Series A. Physical Sciences, V. 38, 1979
Contribution - Hokkaido. University, Sapporo, Institute of Low
Temperature Science, no. 2181, 1979

SUMMARY

... Uniaxial compression tests were made on sea ice ... to obtain the relations of the compressive strength with the length of a specimen and a frictional resistance between a load platen and the end of the specimen. Between a load platen and the end of the specimen a sandscreen was placed to generate a large frictional resistance, while a stainless steel sheet was placed to generate a small one ... the strength measured by using a sandscreen was larger than that obtained by using a stainless steel sheet at each length...

KEY WORD	CLASSIFICATION
Ice Technology	Uniaxial Compressive Strength of Sea Ice

SOURCE

Nuttall, J. B.
"Sea Ice Tests"
Calgary, Distributed by APOA, 1971
Beaufort Sea Pressure Ridge and Ice Island Scouring
Report no. 2

SUMMARY

This report presents the results of tests on Sipre core samples of ice received from Gulf Oil Canada Ltd. on May 6, 1971 and tested in the laboratory of the Civil Engineering Department, University of Alberta. ...Thin sections were made from each of the samples and photographs of these are included here. The small half cylinders where tested for salinity, and crystal orientation was measured for five of the six samples. No strength tests were carried out on short cylindrical samples; all were tested for compressive strength and salinity. The long cylindrical samples were tested for compressive strength, generally two tests from each specimen, and all were tested for salinity. Crystal orientation was measured for 11 of the 15 samples. All samples were stored and tested at -10 deg. C.

KEY WORD	CLASSIFICATION
Ice Technology	Sea Ice Tests

SOURCE

Palmer, A. C.; Goodman, D. J.; Ashby, M. F.; Evans, A. G.;
Hutchinson, J. W.; Ponter, A.R.S.
"Fracture and Its Role in Determining Ice Forces on Offshore Structures"
Proceedings of the Second Symposium on Applied Glaciology
held in New Hampshire, USA, 23-27 August 1982. Annals of
glaciology, v. 4, 1983

SUMMARY

One of the most conspicuous phenomena in the Arctic is the fracture of sea ice. It is scarcely possible to travel far without seeing a variety of fracture forms, produced both by natural processes and by human activity. At strain-rates below about .0001/s, deformation is dominated by creep, but at higher strain-rates fracture is much more important. One of the reasons for this is the very low fracture toughness of ice. The movements of ice in contact with offshore structures often induce strain-rates well beyond the level operate in the fracture regime, and it is fracture processes which will determine the design loads. We consider the different modes of repeated fracture that will occcur, and classify them into distinct mechanisms of crushing, spalling, and radial and circumferential cracking. Experimental and field observations are plotted on a deformation mode map. A theoretical treatment of radial cracking conforms that very low loads can propagate cracks to long distances; these loads are small by comparison with those calculated from theoretical models that treat ice as a plastically-deforming continuum.

KEY WORD	**CLASSIFICATION**
Ice Technology	Fracture of Sea Ice

SOURCE

Prodanovic, A.
"Model Tests of Ice Rubble Strength"
POAC 79: The Fifth International Conference on Port and Ocean
Engineering under Arctic Conditions, at the Norwegian Institute
of Technology, August 13-18, 1979, proceedings, v. 1,

SUMMARY

Ice rubble is a contiguous, random collection of ice pieces which accumulated in forms known as first-year ice poressure ridges and ice rubble fields. ...On a sufficiently large scale, ice rubble can be considered homogeneous and isotropic, making model studies of its gross mechanical properties possible. A series of direct shear tests were carried out to determine the strength of unconsolidated, saline ice rubble modeled at a scale of 1 to 50. Also, the pressures exerted by simulated floating ice rubble fields advancing against cylindrical structures were measured. It was found that the shear strength increases approximately linearly with confinement (ice rubble acts as a Mohr-Coulomb material). The strength data were then related to the ice rubble-field pressures measured in the study.

KEY WORD	CLASSIFICATION
Ice Technology	Ice Rubble - Strength

SOURCE

Sackinger, W. M.; Nelson, R. D.
"Ice Stresses near Grounded Structures"
POAC 79: The Fifth International Conference on Port and Ocean Engineering under Arctic Conditions, at the Norwegian Institute of Technology, August 13-18, 1979, proceedings, v. 1,

SUMMARY

Naturally-occurring sea ice stresses were measured seaward of a grounded pressure ridge. On several occasions, wind-generated tensile stresses were recorded, causing crack formation in some instances. Based upon this data, it appears that the tensile strength of annual ice, in-situ, can be as high as 830 to 970 kPa (120-140 psi) during spring conditions. During breakup of the ice sheet, many stress events were recorded. ...Stresses during the plate interactions of breakup were localized to a range of less than 100 meters, which suggests that ice stresses around a grounded structure as the ice fails may be localized, rather than uniformly distributed.

KEY WORD	CLASSIFICATION
Ice Technology	Ice Stresses Near Grounded Structure

SOURCE

Sackinger, W. M.; Nelson, R. D.
"Measurements of Sea-Ice Stresses Near Grounded Obstacles"
Journal of Energy Resoures Technology, v. 102, Sept. 1980

SUMMARY

Stresses were measured in multiyear sea ice near a grounded floe island. Compressive stresses as high as 250 psi (1.72 MPa) were observed, in the form of impulses. A second installation in annual sea ice near a grounded pressure ridge showed tensile stress of 100 psi (0.69 MPa), followed by crack formation. These stresses were localized to a range of the order of 100m. Localized compressive stresses in multiyear ice near grounded offshore structures may exceed 250 psi (1.72 MPA), and impulsive loading should be expected.

KEY WORD	CLASSIFICATION
Ice Technology	Sea-Ice Stresses Near Grounded Obstacles

SOURCE

Schwarz, J.; Weeks, W. F.
"Engineering Properties of Sea Ice"
Proceedings - Symposium on Applied Glaciology, Cambridge, 13 - 17 September 1976. Journal of Glaciology, V. 19, No. 81

SUMMARY

As the continental shelves of the Arctic become important as source areas for the oil and minerals required by human society, sea ice becomes an increasing challenge to engineers. The present paper starts with a consideration of the different fields of engineering which require information on sea ice with the tasks ranging from the design of ice-breaking ships to Arctic drilling platforms and man-made ice islands. Then the structure of sea ice is described as it influences the observed variations in physical properties. Next the status of our knowledge of the physical properties important to engineering is reviewed. Properties discussed include mechanical properties (compressive, tensile, shear and flexural strengths; dynamic and static elastic moduli; Poisson's ratio), friction and adhesion, thermal properties (specific and latent heats, thermal conductivity and diffusivity, density) and finally electromagnetic properties (dielectric permittivity and loss, resistivity). Particular attention is given to parameters such as temperature, strain-rate, brine volume, and loading direction as they affect property variations. Gaps, contradictions in the data, and inadequacies in testing techniques are pointed out. Finally suggestions are made for future research, especially for more basic laboratory studies designed to provide the data base upon which further theoretical developments as well as field studies can be built.

KEY WORD	CLASSIFICATION
Ice Technology	Engineering Properties of Sea Ice

SOURCE

Sinha, N. K.
"Rheology of Columnar-Grained Ice"
Experimental Mechanics, Vol. 18, No. 12, 464-470

SUMMARY

Creep of columnar-grained ice, under uniaxial compressive force normal to the columns, is shown to be composed of an instantaneous elastic response followed by a delayed elastic and viscous deformation. Both the delayed elastic and viscous strains are shown to have equal activation energies. Thus, this ice can be considered as a thermo-rheologically simple material with a nonlinear stress dependence. A simple phenomenological relationship has been developed that can be used for further analysis of the creep compliance function presented in a normalized form.

KEY WORD	CLASSIFICATION
Ice Technology	Rheology of Columnar - Grained Ice

SOURCE

Sinha, N. K.
"Short-Term Rheology of Polycrystalline Ice"
Journal of Geology, Vol. 21, No. 85

SUMMARY

Deformation characteristics of polycrystalline ice and their dependence on time, temperature, and stress have been analysed on the basis of a phenomenological relation which describes creep in terms of initial elastic, delayed elastic, and permanent strain. It is shown that the effective modulus of ice observed in the laboratory or in the field can be examined on the basis of this model. The model also provides a basis on which the observed flow law of ice can be examined conveniently. Some apparent inconsistencies in the results of earlier investigations of the mechanical property of ice appear to be reconciled by the model.

KEY WORD	CLASSIFICATION
Ice Technology	Rheology of Polycrystalline Ice

SOURCE

Sinha, N. K.
"Rate Sensitivity of Compressive Strength of Columnar-Grained Ice"
Experimental Mechanics, Vol. 21, No. 6
June 1981

SUMMARY

Methods of selecting and preparing specimens and details of test procedures, including those for microstructural examination, are described for the investigation of uniaxial compressive strength of columnar-grained ice. It is shown that specimen strain rates are not constant for constant cross-head -displacement rate, and that consequently the results are not representative of the constant strain-rate condition. Analysis shows that constant cross-head-displacement tests are more closely representative of the constant stress-rate condition. The paper also discusses failure strains, failure times, mode of failure and possible dependence of strength results on stiffness of the test system.

KEY WORD	CLASSIFICATION
Ice Technology	Rate Sensitivity of Compressive Strength of Columnar - Grained Ice

SOURCE

Sinha, N. K.
"Comparative Study of Ice Strength Data"
Ottawa: National Research Council of Canada, Division of Building Research

SUMMARY

A review of strain rate sensitivity of uniaxial compressive yield strength of polycrystalline ice indicates that the results obtained by different investigators reflect the stiffness of the corresponding test systems. It is shown that the softer the system the softer is the effective response of the material. Using the concept of failure modulus, it is shown that brittle-like splitting failures do not indicate pure elastic loading conditions, and that apparent ductile-to-brittle transition depends on the response of the test system. Thus, much of the scatter in available results for the same type of ice is attributable to difference in the response of the different test systems.

KEY WORD	CLASSIFICATION
Ice Technology	Ice Strength Data

SOURCE

Sinha, N. K.
"Constant Stress Rate Deformation Modulus of Ice"
Ottawa: National Research Council of Canada, Division of Building Research

SUMMARY

A generalized, constant-stress creep equation incorporating the effect of grain size for polycrystalline materials is presented and used in calculating ice stress-strain diagrams for constant stress rate loading conditions. It is shown that the effective modulus, determined from the initial part of these diagrams, increases with increase in rate of loading, increase in grain size, and decrease in temperature, in agreement with general observations on ice. Measurements on fresh-water and sea ice are presented and compared with the theoretical predictions. It is shown that the lower effective modulus for sea ice in comparison with that for fresh-water lake or river ice under similar conditions of temperature and rate of loading is due mainly to the difference in the microstructure and not necessarily to the salt content of sea ice. Sub-grains are shown to be a significant factor in controlling the deformation behaviour of ice.

KEY WORD	CLASSIFICATION
Ice Technology	Constant Stress Rate Deformation Modulus of Ice

SOURCE

Sinha, N. K.
"Creep Model of Ice for Monotonically Increasing Stress"
Cold Regions Science and Technology, 8(1983) 25-33, Elsevier Science
Publishers B.V., Amsterdam

SUMMARY

A numerical integration method of predicting the strain path corresponding to a given stress history, and hence the stress-strain relation, has been developed for polycrystalline materials like ice at high homologous temperatures. The method is based on a generalized creep equation incorporating the grain size effect and predicts strain in terms of elastic, delayed-elastic, and viscous or permanent strains. The theory has been tested successfully during strength tests of ice in the temperature range of -5 to -30°C. The monotonous increase in strain rate observed during testing under conditions of constant cross-head displacement rate can now be explained analytically.

KEY WORD	CLASSIFICATION
Ice Technology	Creep Model of Ice

SOURCE

Sinha, N. K.
"Field Test 1 of Compressive Strength of First-Year Sea Ice"
Annals of Glaciology 4, International Glaciology Society

SUMMARY

A test program undertaken in April 1981 on the uniaxial compressive strength of freshly recovered first-year columnar-grained sea ice at a portable field laboratory floating on top of the ice cover in Eclipse Sound, Baffin Island, Canadian Arctic, is reported. Using a small battery-operated test machine, both vertical and horizontal samples were tested so that the load could be applied either parallel or perpendicular to the axis of the columns. Rate sensitivity of the observed strength is discussed in terms of measured average strain-rate and average stress-rate to upper yield or failure. Strain and time aspects of the test results are considered as well. Although vertical samples showed considerably greater strength than horizontal samples, no significant differences were detected in the failure strains. Examination of the interdependence of failure stress and failure time revealed certain anomalies in the results for vertical samples that could be linked to the performance characteristics of the test machine. As such problems could be common to any test systems, methods of analysis are proposed for rational examination of the results.

KEY WORD	CLASSIFICATION
Ice Technology	Compressive Strength of First Year Sea Ice

SOURCE

Sinha, N. K.
"Field Tests on Rate Sensitivity of Vertical Strength and Deformation of First-Year Columnar-Grained Sea Ice"
Ottawa: National Research Council of Canada, Division of Building Research

SUMMARY

Observations on rate sensitivity of uniaxial, unconfined compressive strength and deformation of freshly recovered columnar-grained first-year sea ice are described. Loads were applied parallel to the axis of the columns over a wide range of displacement rates, using a portable test machine in a field laboratory at Mould Bay in the western High Arctic of Canada. Results are analysed in terms of measured stress and strain rate to peak stress. Strengths up to 16 $MN.m^{-2}$ at -10°ɣ were obtained, with failure strains in the range of 0.1 to 0.3 percent.

KEY WORD	CLASSIFICATION
Ice Technology	Vertical Strength and Deformation of First-Year Columnar-Grained Sea Ice

SOURCE

Sodhi, D.S.
"Buckling Analysis of Wedge-Shaped Floating Ice Sheets"
POAC 79: The Fifth International Conference on Port and
Ocean Engineering under Arctic Conditions, at the Norwegian
Institute of Technology, August 13-18, 1979, proceedings, v.1

SUMMARY

A buckling analysis for semi-infinite wedge-shaped floating ice sheets is presented, considering a radial stress field for the in-plane stresses. The buckling load and buckling pressure are computed for varying ice sheet geometry and boundary conditions. The results of this analysis are close to those of earlier analyses for semi-infinite ice sheets and tapered beams.

KEY WORD	CLASSIFICATION
Ice Technology	Buckling Analysis of Floating Ice Sheets

SOURCE

Squire, V.A.; Martin, S.
"A Field Study of the Physical Properties, Response to Swell, and
Subsequent Fracture of a Single Ice Floe in the Winter Bering Sea
Seattle: Departments of Atmospheric Sciences and Oceanography, 1980
Scientific report - U.S. Office of Naval Research, no. 18

SUMMARY

Surface strain and vertical heave response experiments were conducted for a single floe within the marginal ice zone of the winter Bering Sea. The strain was measured using an array of three strain meters placed in a 120 deg. rosette configuration, and the heave was computed from simultaneous records of vertical acceleration on the floe and in the water around the floe. Physical properties studies and underwater traverses by divers were also carried out for the floe. The data are presented and interpreted in the light of the subsequent floe fracture; the mean fracture strain amplitude epsilon is found to lie between 44 and 85 microstrain. A discussion of the directionality of the wave energy during the experiment is also given.

KEY WORD	CLASSIFICATION
Ice Technology	Field Study of a Single Ice Floe

SOURCE

Svec, O. J.; Frederking, R. M. W.
"Cantilever Beam Tests in an Ice Cover: Influence of Plate Effects at the Root"
Cold Regions Science and Technology, 4(1981)93-101, Elsevier Scientific Publishing Company, Amsterdam, 1981

SUMMARY

The flexural behaviour of ice covers is often determined by in situ cantilever beam tests. Finite element analysis of such test geometries was used to investigate the influence of the elastic connection between the beam and the ice cover. Where beam lengths were short, i.e., less than ten times the ice thickness, the finite element analysis showed that deflection and moment distribution differ substantially from that predicted, assuming a clamped cantilever beam. Results of full-scale experiments performed on beams of various lengths and widths confirmed that the finite element solution best describes the measured deflections.

KEY WORD	CLASSIFICATION
Ice Technology	Cantilever Beam Tests In An Ice Cover

SOURCE

Tabata, T.; Nohguchi, Y.
"Failure of Sea Ice by Repeated Compression"
Physics and Mechanics of Ice, papers
International Union of Theoretical and Applied Mechanics
Symposium, Technical University of Denmark, Copenhagen,
August 6-10, 1979. Edited by Per Tryde, New York,
Springer-Verlas, 1980.

SUMMARY

Sea ice samples of Lake Sarama, Hokkaido, Japan, and Barrow, Alaska were subjected to two uniaxial compression tests: the normal compression test and the fracture test in which a cyclically changing load was applied to a sample so that compression and stress relaxation were repeated between two fixed levels of stress until the sample fractured ... The duration of time for a sample to fracture decreased with an increase in average stress or temperature or both. In the latter test ... the total amount of mechanical work for a fracture to take place is much larger than that by the former test.

KEY WORD	CLASSIFICATION
Ice Technology	Failure of Sea ice By Repeated Compression

SOURCE

Tehrany, A. R. A.
"Fracture Toughness of Fresh Water Ice and Saline Ice"
Memorial University of Newfoundland, St. John's, Newfoundland
1983

SUMMARY

The critical stress intensity factor, K_{1C}, of articially grown fresh water ice was measured by means of a three point bend test on an edge notched rectangular specimen (22.86 cm x 5.08 cm x 2.54 cm) as a function of the cross head speed, grain size, and temperature. The results for fresh water ice showed that K_{1C} increases as the test temperature and cross head speed decreases. The results showed that the grain size has a pronounced effect on the value of the $K_{1C}X$, as the grain size increases so does the value of stress intensity factor (K_{1C}).

A special freezing chamber was designed to produce artifical grown sea ice with a constant brine volume. The critical stress intensity factor, K_{1C}, for artificially grown saline ice was measured at -4°C, -7°C, -11°C, and -20°C for cross head speeds of 2.5 mm/min., 5 mm/min., and 50 mm/min. As for fresh water ice the K_{1C} was strongly dependent on the test temperature, cross head speed, and grain size of the specimen.

Finally the non-linear fracture toughness of saline ice was examined, and the strain energy release rate (G), and the yield stress for each ice specimen was calculated and is reported.

Details of the crystal structure and the Young's modulus for saline ice, together with a theory of non-linear fracture toughness, are presented in the Appendix.

KEY WORD	CLASSIFICATION
Ice Technology	Fracture Toughness of Ice

SOURCE

Timco, G.W.; Frederking, R.M.W.
"Compressive Strength of Multi-Year Ridge Ice"
(Proceedings of a Workshop on Sea Ice Ridging and Pile-up,
22-24 October, 1980, Calgary, Alberta, Technical Memorandum
- Canada. National Research Council, Associate Committee on
Geotechnical Research, no. 134

SUMMARY

During the 1979-80 winter trials of the Canmar Kigoriak, the authors performed a series of ice property measurements which to a large extent dealt with tests of the uniaxial compressive strength of the ice. The ice which was tested included a number of samples of multi-year ice which were collected by Canmar during a prope into the polar pack ice with the Kigoriak in October 1979. The results of these tests are presented here. In general, it was found that the compressive strength of this ice was lower than the strength of the first year ice encountered during the trials.

KEY WORD	CLASSIFICATION
Ice Technology	Multi-Year Ridge Ice

SOURCE

Timco, G. W.; Frederking, R. M. W.
"Comparative Strengths of Fresh Water Ice"
Cold Regions Science and Technology 6(1982) 21-27, Elsevier Scientific
Publishing Company, Amsterdam, 1982

SUMMARY

In order to gain a quantitative comparison among the various mechanical properties of ice, a series of tests was performed on fresh water ice in which several of the mechanical properties were tested under identical experimental conditions. In particular, the tests were standardized with respect to ice growth conditions, ice type, grain size and orientation, sample size, test temperature and strain rate. The average results of the test were: flexural strength - cantilever beam = 770 ± 150 kPa; flexural strength - simple beam (top tension) = 2200 ± 320 kPa; flexural strength - simple beam (bottom tension) = 1770 ± 190 kPa; fracture toughness = 83 ± 7 kPa $m^{1/2}$; shear strength = 500 ± 220 kPa; compressive strength (horizontal loading) = 4400 ± 700 kPa and strain modulus - cantilever beams = 1.6 ± 0.4 GPa. Since most of the tests were performed using a portable compression test machine, the strength values can serve as baseline values for comparison with field results.

KEY WORD	CLASSIFICATION
Ice Technology	Strengths of Fresh Water Ice

SOURCE

Timco, G. W.; Frederking, R. M. W.
"Flexural Strength and Fracture Toughness of Sea Ice"
Cold Regions Science and Technology 8(1982) 35-41, Elsevier Scientific
Publishers B.V, Amsterdam, 1982

SUMMARY

A series of mid-winter experiments were carried out on the ice in the rubble field around Tarsiut Island in the Beaufort Sea. The tests included grain structure determination, salinity and density of the ice, small beam flexural strength and fracture toughness. Typical values for flexural strength and fracture toughness were 0.6 - 1.0 MPa and 100-140 kPa $m^{1/2}$ respectively. Both properties were dependent on brine volume and depth in the ice sheet. In comparing these results with identical tests on fine-grained freshwater ice it was found that for comparable loading conditions, the strength of the sea ice was significantly lower than the strength of the freshwater ice, whereas the fracture toughness of the sea ice was higher than the fracture toughness of the freshwater ice.

KEY WORD	CLASSIFICATION
Ice Technology	Flexural Strength and Fracture Toughness of Sea Ice

SOURCE

Tinawi, R.; Murat, J. R.
"Creep of Floating Sea-Ice Sheets - A Finite Element Formulation
POAC 79: The Fifth International Conference on Port and
Ocean Engineering under Arctic Conditions, at the Norwegian
Institute of Technology, August 13-18, 1979, proceedings, v.1

SUMMARY

A finite element program has been developed for the study of floating ice sheets. ...The non-homogenity of the material, due to variation in salinity and temperature, has been considered by the program. The effect of such a variation of properties is studied for short term loading where maximum stresses need to be known. ...A stationary creep law of the power form with temperature dependant coefficient is proposed. Finally the developed program is used to predict the time required to reach free board deflection for different values of loads and ice thicknesses.

KEY WORD	CLASSIFICATION
Ice Technology	Creep of Floating Sea-Ice Sheets

SOURCE

Tryde, P.
"Flexural and Uniaxial Compression Strength of Sea Ice in Danish Waters"
POAC 79: The Fifth International Conference on Port and Ocean
Engineering under Arctic Conditions, at the Norwegian Institute
of Technology, August 13-18, 1979, proceedings, v. 1,

SUMMARY

The paper deals with measurements of flexural and uniaxial compression strength of sea ice in Denmark during the winter 1978-79. The tests show that the average uniaxial compression strength is 1250 kN/square m, i.e. 25% higher than the hitherto assumed value of 1000 kN/square m. ...The average flexural strength is 130 kN/square m, which is lower than the expected value of 1/3-1/5 of the uniaxial compression strength. This may be explained by the fact that in the simple supported beam of ice being tested, the rupture is governed by tension at the bottom of the beam, where the ice is weak due to the high temperature around -1 deg...

KEY WORD	CLASSIFICATION
Ice Technology	Compression Strength of Sea Ice in Danish Waters

SOURCE

Urabe, N.; Yoshitake, A.; Iwasaki, T.; Kawahara, M.
"Parameters on Fracture Strength of Sea Ice"
Trans ASME, J. Energy Resour. Technol., 105 (1983)1, March.

SUMMARY

Compressive crushing strength on brackish ice and fracture toughness value on sea ice were measured as parameters associated with fracture strength of ice. The compressive crushing strength depends on salinity, temperature and strain rate. At constant salinity and temperature, the strength increased with increase in strain rate and reached maximum value at about a strain rate of 0.001/s, then decreased with increase in strain rate. An empirical equation to estimate the compressive crushing strength was derived as a function of brine volume, temperature and strain rate.

KEY WORD	CLASSIFICATION
Ice Technology	Parameters on Fracture Strength of Sea Ice

SOURCE

Wadhams, P.
"The Flexural Failure of Hummock Fields and Large Floes at the Summer Ice Edge in the Beaufort Sea"
Sponsor: Dome Petroleum Limited
1981

SUMMARY

... A theory for the flexural response of a uniform floating ice raft to wave action has been developed at SPRI and tested against experimental data from the Labrador Sea (first year floes), Greenland Sea (first and multi year floes, ice island), Bering Sea (thin first year ice) and Antarctic (tabular icebergs). The theory enables us to predict the maximum raft diameter as a function of wave height and period. Furthermore, theory and experimental data on the decay rate of waves in an icefield enable us to calculate how near to the ice edge the EIF must come before suffering fracture. In this report we use as wave data the hindcast wave statistics which we use to compute the effect of Beaufort Sea waves on EIF's of various dimensions. The likelihood of flexural failure is estimated and the maximum sizes of the fragments computed ...

KEY WORD	CLASSIFICATION
Ice Technology	Flexure Failure of Hummock Fields and Large Floes

SOURCE

Wang, Y. S.
"Crystallographic Studies and Strength Tests of Field Ice in the Alaskan Beaufort Sea"
Ocean Engineering under Arctic Conditions, at the Norwegian Institute of Technology, August 13-18, 1979, proceedings, v.1

SUMMARY

A program of field ice crystallography and strength testing was conducted ... on ice samples collected near the Prudhoe Bay west dock and near Reindeer Island, abour nine miles north of the dock. Additional ice samples were collected at several other locations for later laboratory tests. The crystallographic study showed that sea ice at different locations could be quite different in structure...

KEY WORD	CLASSIFICATION
Ice Technology	Crystallographic Studies and Strength Tests

SOURCE

Weeks, W.F.
"Sea Ice Properties and Geometry"
AIDJEX Bulletin, No. 34, Dec. 1976

SUMMARY

This paper discusses what is known of the six physical properties of sea ice (strength, modulus, Poisson's ration, density, friction, and adhesion) that are believed to be most important in problems related to year round offshore operations in the high Arctic. Also discusses ice thickness and pressure ridges.

KEY WORD	CLASSIFICATION
Ice Technology	Sea Ice Properties and Geometry

SOURCE

Weeks, W.F.; Ackley, S. F.
"The Growth, Structure, and Properties of Sea Ice"
U.S. Army Cold Regions Research and Engineering Laboratory, Hanover,
New Hampshire, 1982

SUMMARY

This monograph describes in some detail the current state of knowledge of the observed variations in the structural characteristics (grain size, crystal orientation, brine layer spacing) and composition (brine, gas and solid salts) of sea ice as well as the presumed causes of these variations. The importance of these variations in controlling the large observed changes in the mechanical, thermal and electrical properties of sea ice is also discussed.

KEY WORD	CLASSIFICATION
Ice Technology	Properties of Sea Ice

ICE TECHNOLOGY

1.2 ICE-STRUCTURE INTERACTION

LIST OF TECHNICAL PUBLICATIONS

ICE-STRUCTURE INTERACTION

Title	Author	Publication	Publication Date	Page No.
Model Tests of Multi-Year Pressure Ridges Moving Onto Conical Structures	Abdelnour, R.	In: Proc. IAHR Int. Symp. on Ice, Quebec, July 27-31, 1981, Quebec, Univ. Laval, 1981, Vol. II.	1981	58
Ice Ride-Up on a Man-Made Island	Abdelnour, R. Sayed, M. Metpe, M.	Fourteenth annual Offshore Technology Conference 1982, proceedings - Dallas: Offshore Technology Conference	1982	59
Conceptual Design of LNG Terminal Bridport Inlet East Site	Acres Consulting Services Limited	January 1982	1982	60
Some Influences of Ice Rubble Field Formations Around Artificial Islands in Deep Water	Allyn, N. Wasilewski, B. R.	Coastal eng., 5(1981)2, 3, Oct.		61
Modelling Ice Rubble Fields Around Arctic Offshore Structures	Allyn, N. F. B. Charpentier, K.	14th Annual Spec of AIME et al Offshore Technology Conf. Houston 83/05/03-06 Proc. Vol. 4	1982	62
Problems in Ice Engineering	Assur, A.	USA Cold Reg Res & Eng Lab, Hanover, NH, Int. Symp on Ice Probl, 3rd, Proc, Dartmouth Coll, Hanover, NH, Aug 18-21, 1975, Publ by Int Assoc of Hydraul Res Comm on Ice Probl, Hanover, NH	1975	63

LIST OF TECHNICAL PUBLICATIONS

ICE-STRUCTURE INTERACTION

Title	Author	Publication	Publication Date	Page No.
Prediction of Ice Forces on Conical Offshore Structures	Bercha, F. G. Danys, J. V.	F. G. Bercha & Assoc. Ltd., Calgary, Alta. Int. Symp. on Ice Probl, 3rd, Proc, Dartmouth Coll, Hanover, NH, Aug 18-21,1975. Publ by Int. Assoc. of Hydraul REs Comm on Ice Probl, Hanover, NH	1975	64
Probabilistic Ice-Structure Interaction Theory	Bercha, F. G. Danys, J. V. Rokne, J. G.	In: Proc. IAHR Symp. on Ice Problems, Luleaa (Sweden), Aug. 1978, Luleaa, Int. Assoc. Hydraul. Res., Section for Ice Problems, 1978, Part I, Ice Forces on Structures	1978	65
Arctic Offshore Deepwater Ice-Structure Interactions	Bercha, F. G. Stenning, D. G.	In: 11th Annual Offshore Technol. Conf., Houston, 1979, Proc. Vol. IV, Paper OTC 3632	1979	66
Effect of Pile-Ups and Rubble Fields on Ice-Structure Interaction Forces	Bercha, F. G. Potter, R. E. Goss, R. D. Ghoneim, G. A.	In: 1980 Offshore Technol. Conf. Houston, Proc. Vol. IV, Dallas, OTC, 1980, Paper OTC 3874	1980	67
Concepts for Ice Management at Arctic LNG Terminal	Cammaert, A. B. Miller, D. R. Gill, R. J.	POAC 79, Int. Conf. on Port and Ocean Eng. Under Arctic Con., 5th, Proc, Univ. of Trondheim, Norw Inst of Technol, Aug 13-18, 1979, Vol. 2	1979	68
Antisymmetric Stress for Sea Ice	Campbell, W. J.	IDJEX Bulletin No. 33, Sept. 1976	1976	69

LIST OF TECHNICAL PUBLICATIONS

ICE-STRUCTURE INTERACTION

Title	Author	Publication	Publication Date	Page No.
Ice Forces on Marine Structures	Croasdale, K. R.	Imp. Oil Ltd., Calgary, Alta. Int. Symp. on Ice Probl, 3rd, Proc, Dartmouth Coll, Hanover, NH, Aug 18-21, 1975. Publ by Int. Assoc of Hydraul Res Comm on Ice Probl, Hanover, NH 1975	1975	70
Ice Forces on Large Marine Structures	Croasdale, K. R. Marcellus, R. W.	In: Proc IAHR Int. Symp. on Ice, Quebec, July 27-31, 1981, Quebec, Univ. Laval, 1981, Vol. II	1981	71
Dynamic Interactions Between Floating Ice and Offshore Structures	Croteau, P.	Report No. UCB/EERC-83/06, Earthquake Engineering Research Centre, Univ. of California, May 1983	1983	72
Summer Ice Floe Impacts Against Caisson-Type Exploratory and Production Platforms	Croteau, P.	3rd Int. Symposium on Offshore Mechanics and Arctic Engineering, New Orleans, LA, Feb. 12-16, 1984 Publ: Journal of Energy Resources Technology, July 19, 1983	1983	73
Effect of Ice and Wave Forces on the Design of Canadian Offshore Lighthouses	Danys, J. V.	Minist of Transp, Ottawa, Ont. Can J Civ Eng V. 2 N. 2 June 1975	1975	74

LIST OF TECHNICAL PUBLICATIONS

ICE-STRUCTURE INTERACTION

Title	Author	Publication	Publication Date	Page No.
Ice Forces on Old and New Offshore Lighthouses in the St. Lawrence Seaway	Danys, J. V.	In: POAC 77, 4th Int. Conf. Port and Ocean. Eng. under Arctic Cond., Mem. Univ. Newfoundland, St. Johns, Sept. 26-30, 1977, St. Johns, Ocean Eng. Inf. Centre, 1978, Vol.1	1978	75
On Wind Induced Static Ice Forces on Offshore Structures	Danys, J. V.	In: POAC 77, 4th Int. Conf. Port and Ocean Eng. under Arctic Cond., Mem. Univ. Newfoundland, St. John's, Sept. 26-30, 1977, St. John's, Ocean Eng. Inf. Centre, 1978, Vol. 2	1978	76
Effect of Hummocked Ice on the Piers of Marine Hydraulic Structures	Dolgopolov, Yu. V. Afanasiev, V. P. Koren'kov, V. A. Panfilov, D. F. Vedeneev, B. E.	Int. Symp. on Ice Probl., 3rd, Proc, Dartmouth Coll, Hanover, NH Published by Int Assoc. of Hydraul Res. Comm on Ice Probl, Hanover, NH	1975	77
Model Experiments to Determine the Forces and Behavior of Moving Ice Fields against a Concrete Drilling Caisson	Dunne, M. A. Edwards, R. Y.	Arctec Canada Limited Imperial Oil Limited Calgary: Distributed by APOA, 1975 APOA project no. 143	1975	78
Model Experiments to Determine the Forces Exerted on Structures by Moving Ice Fields: Final Report	Edwards, R. Y. Lewis, J. W.	ARCTEC Inc. Calgary: Distributed by APOA 1972 APOA Project No. 25: Model Tests to Simulate the Action of Ice on Fixed Structures. Report	1972	79

LIST OF TECHNICAL PUBLICATIONS

ICE-STRUCTURE INTERACTION

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Mathematical Model to Describe the Behavior of a Moving Ice Field Encountering a Conical Structure	Edwards, R. Y. Turcot, P. Wallace, W. G. Poirer, A.	Vol. 2 Model Tests to Assess Adfreeze Effects, Calgary: Dist. by APOA, 1973 APOA Project No. 57: Adfreeze Study Report No. 1, Vol. 2	1973	81
Model Experiments to Determine the Forces Exerted on Structures by Moving Ice Fields (Comparison with Small Prototype Test Results)	Edwards, R. Y. Wallace, W. G. Abdelnour, R.	Arctec Canada Limited Calgary: Distributed by APOA, 1975 APOA Project No. 77: Modelling of Small Cone Prototype Tests	1975	82
Behaviour of Iceberg and Artificial Snow Ice Under High Strain Rates and Impact Loads	El-Tahan, H. Swamidas, A. S. J. Arockiasamy, M. Reddy, D. V.	Faculty of Engineering and Applied Science, Mem. Univ. of Newf., St. John's, Newfoundland, Canada		83
Dynamic Ice Loads on a Lighthouse	Engelbrektson, A.	In: POAC 77, 4th Int. Conf. Port and Ocean Eng. under Arctic Cond., Mem. Univ. Newfoundland, St. John's, Sept. 1977, St. John's, Ocean Eng. Inf. Centre, 1978, Vol. 2	1978	84

LIST OF TECHNICAL PUBLICATIONS

ICE-STRUCTURE INTERACTION

Title	Author	Publication	Publication Date	Page No.
The Ship-Ice Interaction	Enkvist, E. Varsta, P. Riska, K.	In: POAC 79, 5th Int. Conf. Port and Ocean Eng. under Arctic Conditions, Norw. Inst. Technology 1979, Trondheim, Univ. Trondheim, 1979, Procs. Vol. II	1979	85
Basic Study of Offshore Structures in Ice-Affected Waters	Fenco Consultants Limited	Submitted to Kawasaki Steel Corp. Eng. Division, Tokyo, Japan, 1979	1979	86
Laboratory Studies of Ice-Structure Interaction	Frankenstein, G. Sodhi, D. S.	U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH	1980	87
A Model Investigation of Ice Forces on Fixed and Oscillating Cones	Frederking, R. Schwarz, J.	In: Intermaritec '80 Hamburg, Int. Conf. Mar. Sciences and Ocean Eng., Berlin, Tech. Univ. Berlin, 1980	1980	88
Experimental Study of Edge Loading of Ice Plates	Frederking, R. Gold, L. W.	Ottawa: National Research Council of Canada, July 14, 1975	1975	89
Model Tests of Ice Forces on Fixed and Oscillating Cones	Frederking, R. Schwarz, J.	Cold Regions Science and Technology, 6(1982)61-72 November 25, 1982	1982	90
Ice Forces on Marine Structures	Gaither, W.S.	Univ. of Delaware, Newark Permanent Int. SAssn Navigation Congresses-Bul V. 1-2 N. 1	1968-1969	91
Proposed Prestressed Concrete Floating Terminal for Arctic Ocean Service	Gerwick, B. C.	POAC	1975	92

LIST OF TECHNICAL PUBLICATIONS

ICE-STRUCTURE INTERACTION

Title	Author	Publication	Publication Date	Page No.
Full-Scale Impact Tests of Canmar Kogoriak in Thick Ice	Ghoneim, G. A. M. Keinonen, A. J.	Canadian Marine Drilling Ltd., Calgary, Canada	1982	93
Ice Conditions Around Artificial Islands, 1975-1976	Gladwell, R. W.	Imperial Oil Limited Calgary: Distributed by APOA, 1977 APOA Project No. 105: In-situ Pressure Measurements around Artificial Islands in Southern Beaufort Sea - Phase II, Report No. 3	1977	94
A Theoretical Fracture Analysis of the Impact of a Large Ice Floe with a Large Offshore Structure	Hamza, H. Muggeridge, D. B.	Mem. Univ. of Nfld., St. John's, Newfoundland, Canada	1979	95
Ice Forces on Model Bridge Piers	Haynes, F.D., Sodhi, D.S., Kato, K., Hirayama, K.	CRREL Technical Report 83-19	1983	96
Marine Structures and Ships in Ice	Hysing, T.	Performing Org: norske Veritas Research Division; River and Harbor Laboratory P.O. Box 300 N-1322 Hovik, Norway Klaebuveien 153 7034 Trondheim NTH Norway Subfile: MRIS, Proj. Start Date: 1978 Proj. Term. Date: 1980	1978	97
Monocone - A Mobile Gravity Platform for the Arctic Offshore	Jazrawi, W. Khanna, J.	In: POAC 77, 4th Int. Conf. Port and Ocean. Eng. under Arctic Cond., Mem. Univ. Newfoundland, St. Johns, Sept. 26-30, 1977, St. Johns, Ocean Eng. Inf. Centre	1978	98

LIST OF TECHNICAL PUBLICATIONS

ICE-STRUCTURE INTERACTION

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Ice-Structure Interaction - Some Recent Veritas Approaches	Jordaan, I. J. Appleby, J. Fidjestoel, P.	Offshore Technology, Nov.-Dec., 1983, Montreal	1983	99
Measurement of Horizontal and Vertical Ice Loads on Pile Type Structures	Karri, J. Jumppanen, P.	In: Proc. IAHR Int. Symp. on Ice, Quebec, July 27-31, 1981, Quebec, Univ. Laval, 1981 Vol. II	1981	100
Ice Action on Pairs of Cylindrical and Conical Structures	Kato, K. Sodhi, D. S.	CRREL Report 83-25	1983	101
On the Determination of Horizontal Forces a Floating Ice Plate Exerts on a Structure	Kerr, A. D.	CRREL Report 78-15, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, Aug. 1978	1978	102
On the Buckling Force of Floating Ice Plates	Kerr, A. D.	CRREL Report 81-9, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, June 1981	1981	103
Offshore Structures in Arctic Ice	Kivisild, H. R.	Proceedings, Vol. 2 BOSS '76, The Norwegian Institute of Technology, Trondheim, Norway, August 1976	1976	104
Ice Force Prediction Using a Limited Driving Force Approach	Kreider, J. R. Vivatrat, V.	Trans. ASME, J. Energy Resour. Technol., 105(1983)1, March	1983	105
Statistical Prediction of Effective Ice Crushing Stresses on Wide Structures	Kry, P. R.	Imp Oil Ltd., Calgary, Alberta IAHR (Int Assoc for Hydraul Res) Symp on Ice Probl, 5th, Proc, Lulea, Swed, Aug 7-9, 1978 Publ. by IAHR, Delft, Neth, 1978 v. 1	1978	106

LIST OF TECHNICAL PUBLICATIONS

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Ice Forces on Wide Structures	Kry, P. R.	Canadian Geotechnical Journal, Vol. 17, No. 1. pp. 47-113	1980	108
Modular Slope Protection for the Arctic Environment	Leidersdorf, C. B. Potter, R. E. Gerwick, B. C., Jr. Hsu, Y. Y.	Fourteenth Annual Offshore Technology Conference, Houston, Texas, May 3-6, 1982	1982	109
Modeling the Interaction Between Pressure Ridges and Conical Shaped Structures	Lewis, J. W. Croasdale, K. R.	In: Pro. IAHR Symp. on Ice Problems, Lulea (Sweden), Aug. 1978, Lulea, Int. Assoc. Hydraul. Res., Section for Ice Problems, 1978, Part I, Ice Forces on Structures	1978	110
Dynamic Ice-Structure Interaction During Continuous Crushing	Maattanen, M.	Hanover, N. H.: Cold Regions Research and Engineering Laboratory, 1983 CRREL Report, 83-5	1983	111
Ice Design Statistics for the Canadian Beaufort Sea	Marcellus, R. W. Morrison, T. B.	Canadian Marine Engineering Ltd. Dome Petroleum Limited Gulf Canada Resources Inc. Esso Resources Canada Limited Canadian Marine Engineering Ltd.	1982	112

LIST OF TECHNICAL PUBLICATIONS

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Ice Conditions and Ice Defense at Netserk B-44 and Adgo P-25 during the Winter of 1974-75	Metge, M.	Imperial Oil Limited Calgary: Distributed by APOA, 1976 APOA Project No. 104: Measurement of Ice Pressure on Artificial Islands - Phase I, Report No. 1	1976	114
Ice Pressure on Engineering Structures	Michel, B.	CRREL Monograph III Blb, Corps of Engineers, U.S. Army, Hanover, New Hampshire, 1970	1970	115
The Use of Model Ice to Simulate Ice Action on Offshore Structures	Michel, B.	Calgary: Distributed by APOA, 1972 APOA Project No. 41: Evaluation of the Mechanical Properties of Michels Model Ice and Preliminary Ice-Structure Interaction Experiment. Report Contents: Pt. 1 Properties of Model Ice - Pt. 2 Model Ice Action on Structures	1972	116
Ice Pressures Against Structures	National Research Council	Proceedings of a Conference held at Laval University, Quebec, 10-11 November, 1966	1966	117
Interaction of Ice Floes with the Columns of a Semi-Submersible	Noble, P. G. Singh, D.	Fourteenth Annual Offshore Technology Conference, Houston, Texas, May 3-6, 1982	1982	118

LIST OF TECHNICAL PUBLICATIONS

ICE-STRUCTURE INTERACTION

Title	Author	Publication	Publication Date	Page No.
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Model and Field Experiments for Development of Ace (Ice) Resistant Offshore Structures	Oshima, M. Marita, H. Yashima, N. Tabuchi, H.	In: 1980 Offshore Technol. Conf. Houston, Proc. Vol. IV, Dallas, OTC, 1980, Paper OTC 3885	1980	120
Ice Forces on Conical Structures	Pearce, J. C. Strickland, G. E.	In: 11th Annual Offshore Technol. Conf., Houston, Proc. Vol. IV, Paper OTC 3635	1979	121
Ice Force Design Considerations for Conical Offshore Structures	Ralston, T. D.	POAC 77, 4th Int. Conf. Port and Ocean Eng. under Arctic Cond., Mem. Univ. Nfld., St. John's, Ocean Eng. Inf. Centre, 1978, Vol. 2	1978	122
Stochastic Response of a Three-Dimensionl Offshore Tower to Ice Forces	Reddy, D. V. Cheema, P. S. Swamidas, A. S. Haldar, A. K.	Mem. Univ. of Nfld., St. John's Int. Symp. on Ice Probl, 3rd, Proc, Dartmouth Coll, Hanover, NH, Aug 18-21, 1975. Publ by Int. Assoc of Hydraul Res Comm on Ice Probl, Hanover, NH 1975	1975	123
Ice Force Response Spectrum Model Analysis of Offshore Towers	Reddy, D. V. Swamidas, A. S. J. Cheema, P. S.	In: Proc. Third Int. Conf. on Port and Ocean Eng. under Arctic Conditions, Fairbanks, Univ. Alaska, Inst. Mar. Sci., 11-15 Aug. 1975, Fairbanks, Univ. Alaska, 1976, Vol. II, Section 9 - Structures	1976	124

LIST OF TECHNICAL PUBLICATIONS

ICE-STRUCTURE INTERACTION

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Response of an Offshore LPG Storage Platform to Simulated Ice and Wind Forces	Reddy, D. V. Sodhi, D. S. Arockiasamy, M. Haldar, A. K.	In: POAC 77, 4th Int. Conf. Port and Ocean Eng. under Arctic Cond., Mem. Univ Newfoundland, St. Johns, Sept. 26-30, 1977, St. Johns, Ocean Eng. Inf. Centre, 1978, Vol. 1	1978	126
Non-Stationary Response of Offshore Towers to Ice Forces	Reddy, D. V. Arockiasamy, M. Cheema, P. S.	In: POAC 79, 5th Int. Conf. Port and Ocean Eng. under Arctic Conditions, Norw. Inst. Technol., 1979, Trondheim, Univ. Trondheim, 1979, Procs. Vol. II	1979	127
Dynamic Response of Moored Semisubmersible to Bergy Bit Impact, Irregular Wave, Wind and Current Forces	Reddy, D. V. Muggeridge, D. B. Swamidas, A. S. J. (et al)	In: Proc. 14th Annual Offshore Technology Conf., Houston, May 1982, Dallas, Offshore Technol. Conf., Program Dep., 1982, Vol. IV, Paper OTC 4425	1982	128
State-of-Art Review of Basic Ice Problems for a Naval Architect	Riska, K. Varsta, P.	(Espoo, Finland) Technical Research Centre of Finland	1977	129

LIST OF TECHNICAL PUBLICATIONS

ICE-STRUCTURE INTERACTION

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Adfreeze Bonding Between Sea Ice and Offshore Structures	Sackinger, W. M.	Northern Engineer, v. 9, no. 4, Winter 1977	1977	131
Sea Ice Stresses Near Grounded Obstacles	Sackinger, W. M. Nelson, R. D.	In: 11th Annual Offshore Technol. Conf., Houston, 1979, Proc. Vol. IV, Paper OTC 3563	1979	132
Experimental Study of the Compressive Strength of Sea Ice and the Ice Forces on a Circular Pile	Saeki, H. Saito, S. Hamanka, K. Ozaki, A.	Coastal Eng Jpn. V. 19 Dec. 1976	1976	133
Experimental Study on Ice Forces on a Cone-Shaped and an Inclined Pile Structure	Saeki, H. Ono, I. Ozaki, A.	POAC 79: The Fifth International Conference on Port and Ocean Engineering under Arctic Conditions, at the Norwegian Institute of Technology, August 13-18, 1979, proceedings V. 2	1979	134

LIST OF TECHNICAL PUBLICATIONS

ICE-STRUCTURE INTERACTION

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Ice Pressure Measurements at Arnak L-30 and Kannerk G-42	Semeniuk, A.	Imperial Oil Limited Calgary: Distributed by APOA, 1977 APOA project no. 122: In situ ice pressure measurements 1976/77 Report	1977	136
Ice Rubble Field Stability	Shinde, S. B. Wards, R. D.	Fourteenth Annual Offshore Technology Conference, Houston, Texas, May 3-6, 1982	1982	137
Selection of Design Ice Pressures and Application to Impact Load Prediction	Slomski, S. Vivatrat, V.	In: POAC 83, Proc. 7th Int. Conf. on Port and Ocean Eng. under Arctic Conditions, Helsinki, April 1983, Espoo, VTT,	1983	138
Ice Floe Induced Structural Vibrations	Sundararajan, C.	ASME Petrol Div. Engery Technology Conf. Houston, 78/11/05-09 Preprint No. 78-PET-21	1979	139

LIST OF TECHNICAL PUBLICATIONS

ICE-STRUCTURE INTERACTION

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Vertical Lifting Ice Forces Caused by a Rising Water Level, and their Action on a Vertical Slender Structure (Pile)	Tryde, P.	Proceedings of the Second Symposium on Applied Glaciology held in New Hampshire, USA, 23-27 August, 1982 Annals of Glaciology, V. 4	1983	141
Failure Process of Ice Edge Caused by Impact with Ship's Side	Varsta, P. Riska, K.	(Papers - Symposium on Ice, Ships and Winter Navigation, Oulu University, Finland, 16-17 December, 1977. Oulu: Oulu University	1977	142
Small Prototype Cone Tests, Winter 1973-74	Verity, P. H.	Imperial Oil Limited Calgary: Distributed by APOA, 1975 APOA Project No. 65: Small Prototype Cone Test. Report	1975	143
Ice Conditions around Isserk E-27, 1977/78	Vittorators, E. S.	Esso Resources Canada Limited Calgary, Alta. Beaufort E.I.S. reference work, no. RW108	1978	144
Strains and Strain Rates in Sea Ice Indentation	Vivatrat, V.	Fourteenth Annual Offshore Technology Conference, Houston, Texas, May 3-6, 1982	1982	145

LIST OF TECHNICAL PUBLICATIONS

ICE-STRUCTURE INTERACTION

Title	Author	Publication	Publication Date	Page No.
Ice Forces on Simulated Structures	Zabilansky, L. J. Nevel, D. E. Haynes, F. D.	US Army Cold Reg Res & Eng Lab, Hanover, NH Int. Symp. on Ice Probl, 3rd, Proc, Dartmouth Coll, Hanover, NH, Aug 18-21,1975. Publ by Int. Assoc of Hydraul Res Comm on Ice Probl, Hanover, NH 1975	1975	146

SOURCE

Abdelnour, R.
"Model Tests of Multi-Year Pressure Ridges Moving Onto Conical Structures"
In: Proc. IAHR Int. Symp. on Ice, Quebec, July 27-31, 1981,
Quebec, Univ. Laval, 1981, Vol. II.

SUMMARY

An experimental program was carried out to study the interaction of multi-year ridges with 45 degr. conical structures. The cone is to be used as an ice protection system for an Arctic drilling or production platform in relatively deep water. The resulting ice forces and their analysis are discussed. Their correlation with available previous studies are presented. During the study, the effect of the ridge cross section, ice-structure friction factor, the cone water level diameter and the cone positioning for up or down breaking were investigated.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Model Tests Multi-Year Pressure Ridges

SOURCE

Abdelnour, R.; Sayed, M.; Metpe, M.
"Ice Ride-Up on a Man-Made Island"
Fourteenth annual Offshore Technology Conference 1982,
proceedings - Dallas: Offshore Technology Conference,
1982, V. 3

SUMMARY

The potential of ice ride-up on a man made island, in the Beaufort Sea, and the associated ice forces were investigated through a series of model scale experiments in ARCTEC CANADA's synthetic ice basin. The study was carried out in April 1976 for ESSO RESOURCES on behalf of the Arctic Petroleum Operator Association, project number 109. In this paper, the test procedure, the results and their analysis are presented. In this study, the influence of ice thickness, ice properties and the scale factor on the ice ride-up extent over the island slope and ice forces on the Island were investigated. A simple analytical model was also used to correlate the experimental results and evaluate the ice ride-up likelihood for a wide range of ice conditions.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Model Tests Ice Ride Up

SOURCE

Acres Consulting Services Limited
"Conceptual Design of LNG Terminal Bridport Inlet East Site"
January 1982

SUMMARY

At a meeting held in Petro-Canada's offices on June 30, 1981, the Arctic Pilot Project (APP) requested Acres Consulting Services Limited (Acres) to prepare a scope of work and cost estimate for a revised terminal design for the east site at Bridport Inlet, Melville Island. Authorization to proceed with the study was received by letter from Mr. A. F. McDonald dated July 7, 1981.

From the letter and the discussions at the meeting, it was understood that the conceptual design study was to include:

o design of the dock structure and foundations, barge berths and connection facilities

o evaluation of the ice management system for the revised dock design

o assessment of potential permafrost problems due to warm water discharge

The study was undertaken in two phases and a draft report was submitted to the client following the completion of each phase. Phase I was concerned with the conceptual design of a number of dock alternatives and with the evaluation of each in terms of berthing efficiency, ice management, permafrost and other considerations. In Phase II, more detailed study was made of two of the more feasible alternatives identified in Phase I. This study involved layouts, preliminary design and cost estimates.

The present report covers both Phases I and II and incorporates comments and changes resulting from a review of the draft reports by Acres and APP.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Conceptual Design

SOURCE

Allyn, N.; Wasilewski, B. R.
"Some Influences of Ice Rubble Field Formations Around
Artificial Islands in Deep Water"
Coastal eng., 5(1981)2, 3, Oct.

SUMMARY

Some results of recent design studies on the effect of the ice environment on Artificial Production Islands in deep water in the Canadian Beaufort Sea. The ice climate at the 30-m water depth considered for this study is seaward of the landfast ice, so that large ice movements from varying directions can be expected, although the direction of the Beaufort Gyral will dominate. A rubble field formed on the exposed face of the island will be partially free-floating at its furthest extent, but will be fully grounded and highly consolidated in the first few meters of water depth.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Ice Rubble Field

SOURCE

Allyn, N. F. B.; Charpentier, K.
"Modeling Ice Rubble Fields Around Arctic Offshore Structures"
Fourteenth Annual Offshore Technology Conference, Houston, Texas,
May 3-6, 1982

SUMMARY

Ice rubble fields, extensive accumulations of fractured ice broken out of a moving ice sheet, form around most Arctic offshore structures located in a dynamic ice environment. The extent and influence of such a rubble field are principally governed by the water depth, ice movements, properties of the ice and geometry of the structure.

The authors have developed a computer simulation program which calculates the rubble field extent and properties that will accumulate around various offshore structures located in the path of moving ice. Of particular value are statistics on rubble extent, sliding resistance, pressure attenuation and reduction of the force transmitted to the structure. This tool provides the basis for a more rational calculation of force and ice scour reductions, compared to traditional calculations, as well as the basis for an assessment of the operational problems of product export and resupply over and through free floating or grounded rubble. Pre- and post-processors are used to develop statistics on the ice movement data, and to plot the results of rubble extent, rubble crossections, and pressure transmission calculations.

KEY WORD	CLASSIFIATION
Ice Structure Interaction	Modeling Ice Rubble Field

SOURCE

Assur, A.
"Problems in Ice Engineering"
USA Cold Reg Res & Eng Lab, Hanover, NH
Int Symp on Ice Probl, 3rd, Proc, Dartmouth Coll,
 Hanover, NH, Aug 18-21, 1975
Publ. by Int Assoc of Hydraul Res Comm on Ice Probl,
 Hanover, NH, 1975

SUMMARY

The design of large structures in ice infested water such as piers, offshore terminals and platforms is subject to considerable uncertainties due to lack of suitable data and experience. Observations on ships provide clues for some of the most serious problems to be solved. This paper discusses the effect of friction, adfreezing, side pressure and forces on random ice agglomerations. Horizontal ice pressures can stop ships, so "ice pillows" under moderate ice conditions.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Ship Observations

SOURCE

Bercha, F. G.; Danys, J. V.
"Prediction of Ice Forces on Conical Offshore Structures"
F. G. Bercha & Assoc. Ltd., Calgary, Alta.
Int. Symp. on Ice Probl, 3rd, Proc, Dartmouth Coll,
Hanover, NH, Aug 18-21,1975. Publ by Int. Assoc
of Hydraul REs Comm on Ice Probl, Hanover, NH 1975

SUMMARY

An analysis which includes the effects of in plane forces and edge moments, as well as transverse loading, on the forces which ice sheets in a flexural failure mode may exert on conical structures, is developed. The development includes both theoretical and numerical approaches. Using a form of the theory of the flexural failure of a floating ice sheet as a point of departure, heuristic corrections account for the end force and moment effects are obtained. A range of results based on the corrected theory is then corroborated using a finite element simulator having certain refinements over the analytical approach, including a more precise specification of the end actions.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Conical Structures Ice Forces

SOURCE

Bercha, F. G.; Danys, J. V.; Rokne, J. G.
"Probabilistic Ice-Structure Interaction Theory"
In: Proc. IAHR Symp. on Ice Problems, Luleaa (Sweden),
Aug. 1978, Luleaa, Int. Assoc. Hydraul. Res., Section for
Ice Problems, 1978, Part I, Ice Forces on Structures

SUMMARY

The development of a theory for selecting design ice forces for conical and cylindrical bottom-founded offshore structures was carried out utilizing probabilistic analytical methods and associated computational techniques. Flexural and crushing ice sheet failure phenomena were described utilizing extensions of the customary deterministic theories. Methods of probablistic analysis, involving random variable techniques, were utilized to generate a set of probabilistic equations describing each of the pure mode interactions.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Conical and Cylindrical Structures Ice Forces

SOURCE

Bercha, F. G.; Stenning, D. G.
"Arctic Offshore Deepwater Ice-Structure Interactions"
In: 11th Annual Offshore Technol. Conf., Houston,
1979, Proc. Vol. IV, Paper OTC 3632

SUMMARY

A comprehensive theoretical analysis of deepwater arctic ice-structure interactions was partially described in this paper. Following identification of a severity hierarchy of ice formations and associated strengths for the 200 ft. water depth range in the South Beaufort Sea, quasi-static and dynamic interactions of these formations with a steel monocone production platform structure were analyzed.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Deepwater ice Structure

SOURCE

Bercha, F. G.; Potter, R. E.; Goss, R. D.; Ghoneim, G. A.
"Effect of Pile-Ups and Rubble Fields on Ice-Structure Interaction Forces"
In: 1980 Offshore Technol. Conf. Houston, Proc. Vol. IV, Dallas, OTC, 1980, Paper OTC 3874

SUMMARY

Pile-ups and rubble fields adjacent to Arctic offshore structures can have a significant effect on associated ice-structure interaction forces. This effect can be one of force magnification or decrease, depending on certain ice pile (pile-up or rubble field) and interaction characteristics. In this paper, following a description of ice pile kinematics based on previously published work, developed of a new theory of ice pile load capacities and load transfer characteristics is presented and its application to a series of interaction problems is described. Consolidated, unconsolidated and partially consolidated ice piles interposed between sheets, ridges, rubble fields and large structures are considered.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Ice Rubble Field

SOURCE

Cammaert, A. B.; Miller, D. R.; Gill, R. J.
"Concepts for Ice Management at Arctic LNG Terminal"
Acres Consult Serv Ltd., Can
POAC 79, Int. Conf. on Port and Ocean Eng. Under Arctic Cond.,
5th, Proc, Univ. of Trondheim, Norw Inst of Technol, Aug
13-18 1979 Vol. 2. Publ. by Univ of Trondheim, Norw Inst
of Technol, 1979

SUMMARY

As part of the LNG transportation system for the field located on the Sabine Peninsula of Melville Island in Canada, it is proposed to construct a marine terminal at the nearest suitable harbor on the island M-Bridport Inlet which opens into Viscount Melville Sound. Concern is shown for ice management problems anticipated for the terminal area, since the natural ice growth averages 2 m. An analysis of the accelerated ice growth caused by repeated ship passages shows that ice thickness can be as much as 6 m at the end of a normal winter. A comprehensive review on potential ice management techniques is summarized. The technical and economic feasibility of each of the potential solutions is discussed. From these preliminary investigations, it is concluded the use of waste heat in the form of a thermal discharge from the liquefaction process is the most effective and reliable way to inhibit ice accumulation near the terminal.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Ice Management

SOURCE

Campbell, W. J.
"Antisymmetric Stress for Sea Ice"
AIDJEX Bulletin No. 33, Sept. 1976

SUMMARY

Discusses surface stress per unit surface area acting on the top and bottom of ice surfaces.

KEY WORD	CLASSIFICATON
Ice Structure Interaction	Antisymmetric Stress

SOURCE

Croasdale, K. R.
"Ice Forces on Marine Structures"
Imp. Oil Ltd., Calgary, Alta.
Int. Symp. on Ice Probl, 3rd, Proc, Dartmouth Coll,
Hanover, NH, Aug 18-21,1975. Publ by Int. Assoc
of Hydraul Res Comm on Ice Probl, Hanover, NH 1975

SUMMARY

The paper describes how the coastal zones of the Arctic Ocean are subject to severe ice conditions, and marine structures will experience high ice loads. Except in the very shallow areas, ice ridges will govern the design ice load. Sloping structures are able to withstand the extreme loads due to ice ridges, better than vertical sided structures. However, this advantage may be minimized if ice adheres to the structure and/or if ice rubble interferes with the optimum ice failure and ride-up process. In some areas, the impact by massive ice islands, may threaten the survival of the permanent marine structures.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Ice Forces

SOURCE

Croasdale, K. R.; Marcellus, R. W.
"Ice Forces on Large Marine Structures"
In: Proc IAHR Int. Symp. on Ice, Quebec, July
27-31, 1981, Quebec, Univ. Laval, 1981,
Vol. II

SUMMARY

Driving mechanisms in relation to ice forces are reviewed and a method of predicting ice forces on large marine structures is described. The various stages of interaction during collision between a large ice feature and a structure are examined. In the initial stage of interaction the forces are dominated by the dissipation of the kinetic energy of the large ice feature as it is brought to rest. For an island-type structure the kinetic energy of a thick ice features can be dissipated by deformation and scouring of the underwater slopes. An ice/soil interaction model which is being used to quantify these interactions is presented. Once large ice feature has been brought to rest the driving mechanism is made up of wind and current drag plus the pack ice pressure. These steady driving forces are examined.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Ice Forces on Large Marine Structures

SOURCES

Croteau, P.
"Dynamic Interactions Between Floating Ice and Offshore Structures"
Report No. UCB/EERC-83/06, Earthquake Engineering Research Centre,
College of Engineering, University of California, Berkeley, California
May 1983

SUMMARY

Development of oil and gas resources at Arctic and Subarctic latitudes requires engineers to carefully consider the action of ice in designing offshore facilities for these areas. In this study, the interactions between an offshore structure and floating ice are investigated. Attention is directed to the case where ice fails by crushing at the face of the structure. A formulation suitable for investigating the dynamic response of platform systems including floating ice sheets or ice features is developed and applied.

Material properties of freshwater- and sea-ice relevant to the problem are first reviewed and summarized. Korzhavin's crushing formula, which is the basis of the proposed analytical model, is then studied in detail. The theoretical background of plasticity theory and the yield criteria developed for ice, are presented. Empirical definitiions for the strain rate, contact factor and shape factor are reviewed and discussed. A synthetic description of the crushing formula and its parameter definitions is proposed.

An unidirectional finite element for modeling dynamic ice-structure interaction is developed. The element can simulate elastic loading or unloading as well as yielding according to the crushing formula; the effect of strain rate on ice strength is accounted for. This "ice" element is incorporated into a general nonlinear dynamic analysis formulation which may include the offshore structure, the surrounding seawater in terms of added masses, the foundation in terms of frequency-independent springs, dashpots and virtual soil masses, and the mass of the floating ice feature with its hydrodynamic added mass.

Three types of problems are studied in order to demonstrate the effectiveness of the formulation and to gain some insights into the physical phenomena: the impact of large ice floes against fixed platforms, the response of slender structures subjected to continuous crushing by a uniform ice sheet and the earthquake response of an offshore structure in the presence of floating ice.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Dynamic Interactions

SOURCES

Croteau, P.; Rojansky, M.; Gerwick, B. C.
"Summer Ice Floe Impacts Against Caisson-Type Exploratory
and Production Platforms"
Third International Symposium on Offshore Mechanics and Arctic Engineering,
New Orleans, LA, February 12-16, 1984
Published: Journal of Energy Resources Technology, July 19, 1983

SUMMARY

Collisions of large floes against a "typical" gravity-type exploratory drilling platform are simulated. The structure is assumed to have vertical wals and to rest in 10 to 20 meters of water. Under these conditions, it is found that a static approach may not be sufficient to properly describe the interaction and a dynamic analysis is particularly useful in analysing for extreme design events when a limited permanent deformation of the foundation may take place.

Regarding continuous crushing, the model is shown to be effective in describing the large amplitude ice force variations observed during sustained slow velocity crushing against slender structures. The versatility of the finite element formulation is demonstrated by an application to a multi-legged Condeep type platform.

Concerning the earthquake response, the same Condeep gravity structure in 150 meters of water is analyzed under a severe ground motion, with and without an ice cover at the surface of the sea. Under the assumed conditions, the ice is found to have a favorable effect. The amplitudes of global response quantities as well as local member forces are reduced for this particular case.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Ice Floe Impact

SOURCE

Danys, J. V.
"Effect of Ice and Wave Forces on the Design of
Canadian Offshore Lighthouses"
Minist of Transp, Ottawa, Ont.
Can J Civ Eng V. 2 N. 2 June 1975

SUMMARY

Sloped surfaces and cylindrical or conical shapes are used for the substructures of the lightpiers and the ice-structure contact areas are designed as small as practical to reduce ice impact forces.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Offshore Lighthouses

SOURCE

Danys, J. V.
"Ice Forces on Old and New Offshore Lighthouses in the St. Lawrence Seaway"
In: POAC 77, 4th Int. Conf. Port and Ocean. Eng. under Arctic Cond., Mem. Univ. Newfoundland, St. Johns, Sept. 26-30, 1977, St. Johns, Ocean Eng. Inf. Centre, 1978, Vol.1

SUMMARY

At present, theoretical formulae, laboratory testing of small samples, model testing with artificial or natural ice, or mathematical models are not producing reliable results for a practical design as yet. Analysis of old and new structures exposed to ice thrust provides valuable information about actual ice forces, especially in cases where complete or partial failures occurred. In this paper, stability and some failures of sixty-nine old and new lighthouses and lightpiers are analyzed. The results of this analysis are summarized in three tables.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Offshore Lighthouses

SOURCE

Danys, J. V.
"On Wind Induced Static Ice Forces on Offshore Structures"
In: POAC 77, 4th Int. Conf. Port and Ocean Eng.
under Arctic Cond., Mem. Univ. Newfoundland, St.
John's, Sept. 26-30, 1977, St. John's, Ocean Eng. Inf.
Centre, 1978, Vol. 2

SUMMARY

In March 1976, a strong wind blowing along Lac St. Pierre, P.Q., changed its direction twice during a period of 40 hours. Wind induced forces moved the loosened ice cover against the lightpiers which broke the ice leaving "U" shaped paths. The wind induced static ice force exceeded the compressive strength of the ice.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Wind Induced Static Ice Forces

SOURCE

Dolgopolov, Yu. V.; Afanasiev, V. P.; Koren'kov, V.A.;
Panfilov, D. F.; B. E. Vedeneev VNIIG, Leningrad, USSR
"Effect of Hummocked Ice on the Piers of Marine Hydraulic Structures"
Int. Symp. on Ice Probl, 3rd, Proc, Dartmouth Coll, Hanover, NH
Published by Int Assoc. of Hydraul. Res. Comm on Ice Probl,
Hanover, NH
1975

SUMMARY

The interaction of ridged ice with vertical and cone-shaped piers of marine hydraulic structures is described. The ice load on a vertical pier is examined as a summation of forces imposed by solid and disintegrated ice. In the case of a cone-shaped pier the ice load due to solid and disintegrated ice is considered consecutively. Design relationships are proposed. Presented are methods for calculating ice loads on isolated piers of marine hydraulic structures, with rafting of primary ice forms and pressure ridges included. The methods are based on field, experimental and analytical data. 8 refs.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Ridged Ice

SOURCE

Dunne, M. A.; Edwards, R. Y.
"Model Experiments to Determine the Forces and Behavior of Moving Ice Fields against a Concrete Drilling Caisson"
Arctec Canada Limited
Imperial Oil Limited
Calgary: Distributed by APOA, 1975
APOA project no. 143: Model experiments to determine the forces and behavior of moving ice fields against a concrete drilling caisson. Report

SUMMARY

Model tests in synthetic ice were performed at a scale ratio of 1/50, in order to observe the behavior of ice around a model concrete drilling caisson and to determine the magnitude of horizontal and vertical forces exerted thereon. A rubble pile does accumulate against the face of the CDC and continues to grow seaward until the ice cover can no longer support it. A preliminary predictor equation was derived from the data from synthetic model ice tests which may be used to predict full scale forces on the CDC encountering a uniform ice field after pile up forms. ...

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Model Tests Synthetic Ice

SOURCE

Edwards, R. Y.; Lewis, J. W.
"Model Experiments to Determine the Forces Exerted on
Structures by Moving Ice Fields: Final Report"
ARCTEC Inc.
Calgary: Distributed by APOA 1972
APOA Project No. 25: Model Tests to Simulate the
Action of Ice on Fixed Structures. Report

SUMMARY

...The three major areas of investigation were (1) interaction of a conical shaped structure with a field of uniformly thick ice; (2) thick ice; (3) the interaction of a conical shaped structure with an ice field containing multi-year type pressure ridges. During each test, load levels on the models were measured and recorded. Wherever possible the experiments were preceded by the development of mathematical models of the expected interactions.

KEY WORD	CLASSIFIATION
Ice Structure Interaction	Model Tests

SOURCE

Edwards, R. Y.; Kotras, T. V.
"Results of Model Ice Sheet Properties Research"
ARCTEC Inc.
Calgary: Distributed by APOA, 1972
APOA Project No. 40: Evaluation of Mechanical Properties of
Saline Model Ice. Report No. 1, 2

SUMMARY

This report describes the results of experiments to demonstrate that the mechanical properties of model ice sheets formed in the ARCTEC Ice Model Basin may be controlled within the range required for proper modeling of ice sheet-offshore structure interactions. The salinity, temperature, and thickness of model ice sheets were varied widely. The mechanical properties (flexural strength, elastic modulus, and shear strength) were measured in these sheets. The results of the analysis of this data indicate that the ratio of elastic modulus to flexural strength may be maintained at a level in excess of 1000 for flexural strengths as low as 0.1 kg/sq. cm. This implies that modeling ice sheet structure interactions at scales as low as 1/70th is feasible.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Model Ice Sheet

SOURCE

Edwards, R. Y.; Turcot, P.; Wallace, W. G.; Poirer, A.
"Mathematical Model to Describe the Behavior of a
Moving Ice Field Encountering a Conical Structure"
Vol. 2 Model Tests to Assess Adfreeze Effects
Calgary: Distributed by APOA, 1973
APOA Project No. 57: Adfreeze Study Report No. 1, V. 2

SUMMARY

Volume II of the report ... contains three appendices which describe the results of model tests in artificial ice. Their purpose was to assess the effect of adhesion of ice pieces to the surface of a conical structure upon the modes of failure of the ice cover as it impinges on the cone. An additional purpose was to assess the potential increase in magnitude of forces experienced by the structure due to the ice adhesion phenomenon. The tests were overall successful and despite certain incorrect scale factors provided excellent guidance for the engineers preparing the mathematical model. The results indicate that if an adhesion bond becomes established over the entire frontal area of a conical structure the forces which the cone will experience may increase to six times the level which we would estimate for the structure if adfreeze effects were ignored.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Mathematical Model

SOURCE

Edwards, R. Y.; Wallace, W. G.; Abdelnour, R.
"Model Experiments to Determine the Forces Exerted on Structures
by Moving Ice Fields (Comparison with Small Prototype Test Results)"
Arctec Canada Limited
Calgary: Distributed by APOA, 1975
APOA Project No. 77: Modelling of Small Cone Prototype Tests

SUMMARY

Forty-two tests were conducted which consisted of forcing large slabs of synthetic model ice against right circular cones with a slope of 45 deg. There were four model cones which were 1/5th, 1/10th, 1/20th and 1/30th scale models of the prototype tested in the Imperial Oil Ltd. outdoor ice basin. We attempted to scale down the diameter of the prototype cylindrical access tower but due to restrictions in standard stock sizes and the Teflon thickness, this was not achieved exactly in the model tests. ...The model ice sheets ranged in ice thickness between 0.29 and 1.25 inches, in flexural strength 3.58 and 14.21 psi and in elastic modulus from 649 psi to 24293 psi. The ratio of elastic modulus to flexural strength ranged from 180 to 2970. Only for one test series did E/c fall below 1000. ...One of the objectives of this program was to compare for identical conditions, the vertical and horizontal forces measured during ice field impingement. This objective was not achieved. ...

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Model Tests

SOURCE

El-Tahan, H.; Swamidas, A. S. J.; Arockiasamy, M.; Reddy, D. V.
"Behaviour of Iceberg and Artificial Snow Ice Under High Strain
Rates and Impact Loads"
Faculty of Engineering & Applied Science, Memorial University of
Newfoundland, St. John's, Newfoundland, Canada

SUMMARY

The study examines the behaviour of iceberg and artificial snow ice under impact and multiaxial stress conditions, and measures their strengths under various strain rates and confining conditions. The properties and behaviour of artificial snow ice is compared with those of iceberg ice to see if the snow ice can be used as a substitute for iceberg ice when the latter is not available. Three types of tests were carried out on both types of ice, viz., uniaxial compressive, indentation and impact tests and the results presented. Density measurements and crystallographic analysis were also carried out on both snow and iceberg ice.

The average uniaxial compressive strengths of iceberg ice, at a temperature of -5°C for constant strain rates of i) 10^{-3}, ii) 10^{-2}/per sec, and iii) a step function strain rate, were 7.54, 6.6 and 6.97 MPa, respectively. For snow ice the corresponding values were 6.98, 5.62 and 6.73 MPa. The indentation strength of the unconfined iceberg and snow ice blocks at the above strain rates was about 2.3 to 3.1 times the corresponding uniaxial strength. The indentation strength of the confined blocks was about 10 - 20 percent higher than the corresponding strength of unconfined blocks. The impact strength of iceberg and snow ice varied from 12 to 25 MPa.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Icebergs and Artificial Snow

SOURCE

Engelbrektson, A.

"Dynamic Ice Loads on a Lighthouse"
In: POAC 77, 4th Int. Conf. Port and Ocean Eng. under Arctic Cond., Mem. Univ. Newfoundland, St. John's, Sept. 1977, St. John's, Ocean Eng. Inf. Centre, 1978, Vol. 2

SUMMARY

The dynamic response of off-shore lighthouses and similar structures under the influence of ice action may have the appearance not only of shock vibrations caused by impacts from drifting ice, but also of resonance vibrations. According to the actual observations, the resonance vibrations seem to be generated by a fluctuation of the ice force, when an ice sheet is gradually broken by the structure, the constant frequency of fluctuation coinciding with that of the structural vibrations.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Dynamic Response

SOURCE

Enkvist, E.; Varsta, P.; Riska, K.
"The Ship Ice Interaction"
In: POAC 79, 5th Int. Conf. Port and Ocean Eng.
under Arctic Cond., Norw. Inst. Technol.,
1979, Trondheim, Univ. Trondheim, 1979, Procs. Vol. II

SUMMARY

The loading conditions for hull structure design are reviewed. Aspects of ice parameters, failure criteria, ice pressure and total ice load are described. Semi-analytical ice load models are mentioned. Full-scale measurements are discussed and some results presented. Long-term measurements during normal ship operation have proved useful, and results also from such tests with an icebreaker are presented.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Ship/Ice Interaction

SOURCE

Fenco Consultants Limited
"Basic Study of Offshore Structures in Ice-Affected Waters"
Submitted to Kawasaki Steel Corp. Eng. Division, Tokyo, Japan
1979 (proprietory)

SUMMARY

This study outlines in general terms the present state-of-the-art of offshore structures in ice-affected waters. "General" because environmental information which represents a paramount prerequisite for the design of offshore structures is still scarce for most ice covered waters. This applies in particular to ice, its distribution with time and its mechanical and structural properties. Some of the conceptual designs represented in this report are based on assumed environmental data.

It was beyond the scope of this report to deal in detail with the design of each possible structure or even with one particular structure. Instead, a broad spectrum of offshore structures has been presented - supported by some sketches - along with typical ice conditions in which they (the structures) could most likely withstand the expected ice forces.

A novel analytical model was developed representing the sequential breakdown of an ice edge in a crushing mode. This model can be applied to determine static and dynamic forces on slender structures as well as wide rigid structures by employing probability methods.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Offshore Structures State of Art

SOURCE

Frankenstein, G.; Sodhi, D. S.
"Laboratory Studies of Ice-Structure Interaction"
U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH

SUMMARY

Structures placed in ice infested waters are subjected to forces when the ice comes in contact with them. The magnitude of these forces depends on factors such as loading rate, contact area, ice thickness, ice strength, shape of structure, type of ice failure, etc. Laboratory studies are being conducted to better understand the problems associated with ice-structure interaction.

A short discussion on the type of forces that can occur and a review of laboratory studies to determine these forces follows.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Laboratory Studies

SOURCE

Frederking, R. M. W.
"A Model Investigation of Ice Forces on Fixed and Oscillating Cones"
Intermaritec-80, Conference Report/International Conference
on Marine Sciences and Ocean Engineering, Hamburg, Germany, 1980.
Edited by C. Kruppa and G. Clauss. Hamburg: Hamburg Messe und
Congress GmbH, 1980

SUMMARY

A series of model tests were carried out on downward breaking conical structures in the Hamburg Ice Model Basin using low salinity model ice and a warming technique to control the E/sigma ratio. A scale factor of 20:1 was selected for the tests. Fixed cones of angles 15 deg., 30 deg., 45 deg. and 60 deg. were tested in 50 mm thick ice of 60 kPa flexural strength at velocities ranging from 0.01 to 0.05 m/s. The effect of the thickness and flexural strength variations were also investigated for the 45 deg. structure. ...Comparison with information in the literature showed the downward breaking cone to experience lower ice forces than the upward breaking cone. For the oscillating cone further substantial horizontal ice force reductions were achieved.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Model Tests

SOURCE

Frederking, R.; Gold, L. W.
"Experimental Study of Edge Loading of Ice Plates"
Ottawa: National Research Council of Canada, Division of Building Research,
July 14, 1975

SUMMARY

The interaction of an ice cover and a fixed narrow structure was modelled by edge loading large rectangular (0.4 m x 0.5 m) plates of columnar-grained ice. The plates were set on one of the long edges and the load was applied to the opposite edge by means of indentors of widths varying between 12 and 150 mm. Ice plates 25 to 100 mm thick were used. Observations were made of the dependence of the indentations load on indentor width and ice thickness. All loading was within the range of ductile behavior of the ice. The study indicated that the indentation pressure was a function of the width of the indentor, but not of the thickness of the ice plate. The mode of deformation was observed to be primarily two dimensional. The results of this study are in contrast to observations under field conditions, from which it is concluded that the indentation pressure depends on the ratio of the width of the indentor to the thickness of the ice cover. This suggests the presence of an effect which must be given attention in the development of modelling techniques for the ice pressure problem.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Model - Edge Loading

SOURCE

Frederking, R.; Schwarz, J.
"Model Tests of Ice Forces on Fixed and Oscillating Cones"
Cold Regions Science and Technology, 6(1982)61-72
November 25, 1982

SUMMARY

A series of model tests has been carried out on downward breaking conical structures using low salinity model ice. Comparison with information in the literature showed that a downward breaking cone experiences lower ice forces than an upward breaking cone. Fixed cones of angles of 15, 30, 45 and 60 deg were tested in 50-mm-thick ice of 60 kPa flexural strength at velocities ranging from 0.01 to 0.5 m/s. The effects of thickness and flexural strength variations were also investigated. Horizontal forces were observed to increase with increasing velocity. Ice thickness variation was observed to have a stronger influence on the vertical than on the horizontal forces. Vertical and horizontal forces showed a decrease with decreasing flexural strength.

Two test series were run with the 45 deg conical structure arranged so that it oscillated. Horizontal force reductions of up to two thirds were observed.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Model Tests

SOURCE

Gaither, W.S.
"Ice Forces on Marine Structures"
Univ. of Delaware, Newark
Permanent Int. SAssn Navigation Congresses-Bul V. 1-2 N. 1
1968-1969

SUMMARY

Emphasis is on marine structures in the ocean environment but consideration is given to forces resulting from both salt-water ice and fresh-water ice, and ice fields and bergs are taken into account. The types of marine structures on which ice can act are to be understood to include fixed gravity type structures such as breakwaters or caisson, flexible open type structures supported on piles, and floating structures such as ships and buoys. Ice thickness prediction, physical and mechanical properties, forces on structures, and operational considerations are discussed.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Marine Structures

SOURCE

Gerwick, B.C.
"Proposed Prestressed Concrete Floating Terminal
for Arctic Ocean Service"
California University, Berkeley, California, 94720
Available from: Engineering Societies Library, 345
East 47th Street, New York, NY 10017

SUMMARY

Construction of a very large prestressed concrete barge, using its mass, shape, and length in effective combination to continuously break the ice, and able to move laterally in the event of ice-island encounter is contemplated. The first component of a terminal structure, the floating terminal is explored, and possible solutions are suggested for the subsequent components of mooring, riser and offloading connections, needed to make the system viable. Proceedings of the Conference on Concrete Ships and Floating Structures, Sept. 15-19, 1975, University of California, Berkeley.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Floating Structure

SOURCE

Ghoneim, G. A. M.; Keinonen, A. J.
"Full-Scale Impact Tests of Canmar Kogoriak in Thick Ice"
Canadian Marine Drilling Limited, Calgary, Canada

SUMMARY

Canmar Kigoriak was used as a test vehicle to measure ice pressures, loads and ship response in extreme impact interactions while ramming very thick and old ice in the Canadian Beaufort Sea in 1981. Contrary to expectations based on previous experiences such as with the S.S. Manhattan, the global strength of the ship hull may become critical in collisions with extreme ice features such as icebergs and thick multi-year ridges. Furthermore, peculiar behaviour with respect to the velocity dependence of ice loading was noted. Contrary to expectations, the ice forces did not seem to increase with velocity at high velocity levels.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Vessel Impact Tests

SOURCE

Gladwell, R. W.
"Ice Conditions Around Artificial Islands, 1975-1976
Imperial Oil Limited
Calgary: Distributed by APOA, 1977
APOA Project No. 105: In-situ Pressure Measurements around
Artificial Islands in Southern Beaufort Sea - Phase II,
Report No. 3

SUMMARY

... documents the observed ice conditions during the winter of 1975/76 in the vicinity of Netserk F-40, Ikkatok J-17, Netserk B-44, Immerk, Adgo F-28, Adgo C-15 and Adgo P-25. Principal interest was focused on Netserk F-40 from which drilling was being conducted since it was in the deepest water and sustained the most significant ice action. This report marks a significant advance in the understanding of ice-island interaction and documentation of ice failure modes against a wide structure. ...

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Ice Island

SOURCE

Hamza, H.; Muggeridge, D. B.
"A Theoretical Fracture Analysis of the Impact of a Large Ice Floe with a Large Offshore Structure"
Memorial University of Newfoundland, St. John's, Newfoundland, Canada

SUMMARY

In this paper, a simple fracture mechanics approach is presented to calculate the impact forces and pressure generated during the interaction of an ice floe with an offshore structure; the effect of crack length, size of the offshore structure, speed of impact (visco-elastic and brittle response), and the thickness of the ice floe upon the ice impact forces and presssures are included.

The approach and analysis presented in this paper should provide a powerful tool to investigate this ice-structure interaction problem.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Ice Floe Analysis

SOURCE

Haynes, F. D.; Sodhi, D. S.; Kato, K.; Hirayama, K.
"Ice Forces on Model Bridge Piers"
CRREL Report No. 83-19, U.S. Army Cold Regions Research and Engineering
Laboratory, Hanover, New Hampshire,
July 1983

SUMMARY

Small-scale laboratory experiments were conducted on model bridge piers in the CRREL test basin. The experiments were performed by pushing model ice sheets against structures and monitoring the ice forces during the ice/structure interaction. The parameters, varied during the test program, were the geometry of the bridge piers and the velocity, thickness, and flexural strength of the ice. The results are presented in the form of ice forces on sloping and vertical structures with different geometries. During ice action on sloping structures, a phenomenon of transition of failure mode from bending to crushing was observed as the ice velocity was steadily increased.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Model Tests

SOURCE

Hysing, T.
"Marine Structures and Ships in Ice"
Norw. Marit. Res.
1981

SUMMARY

A short description of the Norwegian research project Marine Structures and Ships in Ice (MSSI) is given. Partly based on this work as well as on other ice investigations, characteristic ice conditions, ice properties and analytical models for prediction of the ice loads on Arctic offshore structures are described, and limitations to the applications of theoretical models are discussed.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Research Marine Structures and Ships

SOURCE

Jazrawi, W.; Khanna, J.
"Monocone - A Mobile Gravity Platform for the Arctic Offshore"
In: POAC 77, 4th Int. Conf. Port and Ocean. Eng.
under Arctic Cond., Mem. Univ. Newfoundland, St. Johns,
Sept. 26-30, 1977, St. Johns, Ocean Eng. Inf. Centre,
1978, Vol.1

SUMMARY

This paper discussed a mobile, gravity platform for year-round petroleum operations in the Canadian Beaufort Sea. The "Monocone" is a coined name derived from "Monopod" which alludes to the platform's single structural column rising from the centre of a circular base, and "cone" which refers to a movable conical collar selectively positioned on this column. The conical collar causes the ice to fail in flexure and at minimum loads by maintaining a constant water line diameter in different water depths. Ice and wave forces constitute the main loading conditions and these were developed theoretically and experimentally, the latter in ice model basins and in a wave tank.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Monocone - Gravity Platform

SOURCE

Jordaan, I. J.; Appleby, J.; Fidjestoel, P.
"Ice-Structure Interaction - Some Recent Veritas Approaches"
Offshore Technology, November-December, 1983, Montreal

SUMMARY

The major areas of uncertainty relating to ice loading on structures are identified. These include the arrival rate, the mass and velocity (for discrete features) and the movement rate (for landfast ice). In addition, the morphology, and thickness of the ice feature and the ice properties are variable and have a strong influence on assessments of risk. Probabilistic models are proposed and an integrated risk analysis approach is advocated. Working models for ice-structure interaction are described and some future directions of research are indicated.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Ice Loading

SOURCE

Karri, J.; Jumppanen, P.
"Measurement of Horizontal and Vertical Ice Loads
on Pile Type Structures"
In: Proc. IAHR Int. Symp. on Ice, Quebec,
July 27-31, 1981, Quebec, Univ. Laval, 1981
Vol. II

SUMMARY

Measuring systems for the determination of horizontal and vertical ice loads on different pile type structures are described. The measuring systems for horizontal loads includes special transducers and registration equipment developed for the automatic ice force data collection on sea marks or corresponding structures. Types of collected data are presented. Results from laboratory and field tests on vertical ice loads of piles with different surface properties are also introduced.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Pile Structures

SOURCE

Kato, K.; Sodhi, D. S.
"Ice Action on Pairs of Cylindrical and Conical Structures"
CRREL Report 83-25, U.S. Army Cold Regions Research and Engineering
Laboratory, Hanover, New Hampshire,
September 1983

SUMMARY

Ice action on two cylindrical and conical structures, located side by side, has been investigated in a small-scale experimental study to determine the interference effects on the ice forces generated during ice-structure interaction. The proximity of the two structures changes the mode of ice failure, the magnitude and direction of ice forces on the individual structure, and the dominant frequency of ice force variation. Interference effects were determined by comparing the experimental results of tests at different structure spacings.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Cylindrical and Conical Structures

SOURCE

Kerr, A. D.
"On the Determination of Horizontal Forces a Floating Ice Plate Exerts on a Structure"
CRREL Report 78-15, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, August 1978

SUMMARY

This report first discusses the general approach for calculating the horizontal forces an ice cover exerts on a structure. Ice force determination consists of two parts: (1) the analysis of the in-place forces assuming that the ice cover remains intact and (2) the use of a failure criterion, since an ice force cannot be larger than the force capable of breaking up the ice cover. For an estimate of the large ice force, an elastic plate analysis and a failure criterion are often sufficient. A review of the literature revealed that, in the majority of the analyses, it is assumed that the failure load is directly related to a "crushing strength" of the ice cover. However, observations in the field and tests in the laboratory show that in some instances the ice cover fails by buckling. This report reviews the ice force analyses based on the buckling failure mechanism and points out their shortcomings.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Ice Force Determination

SOURCE

Kerr, A. D.
"On the Buckling Force of Floating Ice Plates"
CRREL Report 81-9, U.S. Army Cold Regions Research and Engineering
Laboratory, Hanover, New Hampshire, June 1981

SUMMARY

The calculation of the largest horizontal force a relatively thin floating ice plate may exert on a structure requires the knowledge of the buckling load for this floating plate. In the published literature on the stability of continuously supported beams and plates, it is usually assumed that this buckling force corresponds to the lowest bifurcation force P_{cr}. However, recent studies indicate that, generally, this is not the case, and this report clarifies the situation for floating ice plates. This problem is first studied on a simple model that exhibits the buckling mechanism of a floating ice plate but is amenable to an exact nonlinear analysis. This study shows that, depending on the ratio of the rigidities of the "liquid" and "plate", the post-buckling branch may rise or drop away from the bifurcation point. Thus P_{cr} may or may not be the actual buckling load. It is also shown that when lift-off of "plate" from the "liquid" takes place, the

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Buckling Force

SOURCE

Kivisild, H. R.
"Offshore Structures in Arctic Ice"
Proceedings, Vol. 2 BOSS '76, The Norwegian Institute of Technology,
Trondheim, Norway, August 1976

SUMMARY

For many centuries, arctic regions have lured explorers and developers who have tried to find new transportation routes, such as the Northwest Passage, who have hunted whales and fur-bearing animals and who have explored and produced natural resources. At present, non-energy minerals, like zinc, lead, silver, gold and asbestos, and energy resources, like oil, gas, coal, uranium and hyro power, are the vital elements. The most important aspect of development in arctic waters and transportation through arctic ice is currently related to oil and gas production and transportation.

In this article, offshore structures in arctic ice will be viewed from the following aspects:

o Arctic Environment
o Designs for Arctic Waters
o Ice Action on Arctic Structures
o Feasibility of Arctic Structures

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Offshore Structures

SOURCE

Kreider, J. R.; Vivatrat, V.
"Ice Force Prediction Using a Limited Driving Force Approach"
Trans. ASME, J. Energy Resour. Technol., 105(1983)1, March

SUMMARY

Importance of environmental driving forces in determining ice loads on Arctic offshore structures. Limits to the environmental driving force in a first-year ice field are analyzed by considering models of ridge formation wind and current driving forces, and irregularities such as leads and tidal cracks. Average driving forces are estimated to be approximately 10-50 kps/ft for far-field, with some local concentration near fixed structures. These order of magnitude estimates are sufficiently less than failure for many ice features to indicate that limited driving force approach may reduce estimated ice loads on Arctic structures.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Driving Force

SOURCE

Kry, P. R.
"Statistical Prediction of Effective Ice Crushing Stresses
on Wide Structures"
Imp Oil Ltd., Calgary, Alberta
IAHR (Int Assoc for Hydraul Res) Symp on Ice Probl,
5th, Proc, Lulea, Swed, Aug 7-9, 1978 Publ. by IAHR,
Delft, Neth, 1978 v. 1

SUMMARY

When an ice sheet moves past a wide structure, the ice failure mechanism is characterized by an irregular contact zone and non-simultaneous failure across the width of the structure. Where sufficient ice motion occurs to prevent formation of a frozen bond between a structure and an ice sheet, this failure mode becomes the design condition for ice crushing against the structure. Due to the nature of the failure, the effective stress across any local region of the failure interface is an irregular function of the ice sheet motion. This observation is developed into the concept of independent zones of crushing in front of a wide structure. It is assumed that as the ice sheet moves past the structure, effective stresses for each zone are developed independently of those in adjacent zones. In each zone, stresses are characterized statistically by the probability of exceedance of a stress level and the mean continuous duration of that exceedance. A statistical summation is used to calculate risk of stress exceedance as a function of stress level and extent of ice movement over the anticipated life of the structure.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Crushing Stresses

SOURCE

Kry, P. R.
"Implications of Structure Width for Design Ice Forces"
Physics and Mechanics of Ice, Papers/International
Union of Theoretical and Applied Mechanics Symposium,
Technical University of Denmark, Copenhagen, August 6-10,
1979. Edited by Per Tryde, New York, Springer-Verlas,
1980

SUMMARY

Hydrocarbon exploration activities in the Canadian Southern Beaufort Sea have provided incentives to further develop our knowledge of ice and its interactions with structures. ...To have sufficient surface area for drilling operations and personnel quarters, these islands represent very wide structures compared to the maximum ice thickness. Their width is further enlarged by ice rubble fields formed by early winter ice motions. ...a rubble field ... provides protection against subsequent ice ride-up. However, the rubble field increases effective structure width and this amplifies forces on the structure. ...forces arise from effective stresses generated by ice failure at the periphery of the rubble field. The extensive width increases the importance of localized failures due to irregularities at the failure interface. Such non-simultaneous failure implies that effective stresses are subject to statistical variations such that design stresses for wide structures are less than peak values apropriate for narrow structures.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Wide Structures

SOURCE

Kry, P. R.
"Third Canadian Geotechnical Colloquium: Ice Forces on Wide Structures"
Esso Resour Can Ltd., Calgary, Alberta
Can Geotech J V. 17, N. 1 Feb. 1980

SUMMARY

Ice forces exerted on wide structures arise from the mechanical processes inherent in particular ice failure modes as environmental stresses move an ice sheet past a structure. Four primary ice failure modes occur against wide structures: flexure, rubble formation, buckling, and crushing. The horizontal forces associated with these modes differ by more than two orders of magnitude depending on structure geometry, ice sheet properties, and ice movement rates. Structure width influences the occurrence of ice failure modes, the ice failure stresses, and the total forces that can be exerted on a structure by an ice sheet. Increased structure width generally results in decreased expected forces per unit width of structure. For crushing, the most serious ice failure mode for island design, increased structure width generates the possibility of nonsimultaneous failure.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Wide Structures

SOURCE

Leidersdorf, C. B.; Potter, R. E.; Gerwick, B. C. Jr.; Hsu, Y. Y.
"Modular Slope Protection for the Arctic Environment"
Fourteenth Annual Offshore Technology Conference, Houston, Texas,
May 3-6, 1982

SUMMARY

Sohio Petroleum Company installed three modular slope protection devices on its Alaskan exploratory drilling islands during 1980 and 1981: a precast concrete pier, a precast concrete seawall, and articulated, linked concrete mats. Developed to test the functional utility and cost effectiveness of modular slope protection concepts in the Arctic, the three experimental systems were designed to conform to five general constraints: (1) adaptability to environmental conditions, (2) resistance to Arctic weathering elements, (3) suitability for rapid deployment, (4) portability, and (5) reusability.

The concrete pier, installed in 11-foot water depth to facilitate drilling rig transfer onto the Sag 7 exploratory island, consists of thirty-eight crib units stacked vertically to form eight gravel-retaining caissons. The concept of vertically-stacked elements offers promise both for portable docks and for production island slope retention.

The 100-foot long seawall test section was developed to protect a drilling pad on Alaska island from wave and ice attack. Unitized concrete elements 12 feet high and 10 feet long are chain-linked to accommodate small displacements with no moment transfer in the event of severe ice impact. By forming a near-vertical peripheral wall, the seawall units reduce the volume of gravel fill required for a given work surface area. Potential future applications include natural island drilling pads, man-made exploratory and production islands, and emergency slope protection.

Articulated, linked concrete mat test sections were installed as slope and toe protection at three locations. Based on ease of installation and performance to date, the concept warrants consideration for both production islands and deep-water exploratory islands.

Potential means of reducing the high cost of concrete for Arctic projects include the use of light-weight aggregate to decrease shipping weights, and the establishment of an efficient casting yard on the North Slope.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Slope Protection

SOURCE

Lewis, J. W.; Croasdale, K. R.
"Modeling the Interaction Between Pressure
Ridges and Conical Shaped Structures"
In: Pro. IAHR Symp. on Ice Problems, Luleaa (Sweden),
Aug. 1978, Luleaa, Int. Assoc. Hydraul. Res., Section
for Ice Problems, 1978, Part I, Ice Forces on Structures

SUMMARY

A series of model-scale experiments were conducted in an ice model basin to assess the feasibility of modeling the interactions between pressure ridged ice fields and bottom-founded structures. The experiments involved: (1) developing methods of constructing model pressure ridges and integrating these with the surrounding plate ice; (2) developing methods to measure the mechanical properties of the model ridges; (3) determining the most likely mode of failure of a pressure ridge; and, (4) determining magnitudes of horizontal and vertical forces exerted by the pressure ridge during breakup against the structure. Most of the experimentation concentrated on studying multi-year pressure ridges of rectangular cross-section interacting with a cone of 45 degr. sloping sides.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Pressure Ridges

SOURCE

Maattanen, M.
"Dynamic Ice-Structure Interaction During Continuous Crushing"
Hanover, N. H.: Cold Regions Research and Engineering Laboratory,
1983
CRREL Report, 83-5

SUMMARY

This report presents the results of dynamic ice-structure interaction model tests conducted at the CRREL Ice Engineering Facility. A flexible, single-pile, bottom-founded offshore structure was simulated by a test pile with about a one-to-ten scale ratio. Urea (instead of sodium chloride) was used as dopant to scale down the ice properties. Six ice fields were frozen and 18 tests carried out. In all cases distinctive dynamic ice-structure interaction vibrations appeared, from which abundant data were collected. In tests with linear ice velocity sweep, sawtooth-shaped ice force fluctuations occurred first. With increasing velocity the natural modes of the test pile were excited, and shifts from one mode to another occurred. The maximum ice force values appeared mostly with low loading rates, but high forces appeared randomly at high ice velocities. As a general trend, ice force maximums, averages and standard deviations decreased with increasing ice velocities. The aspect ratio effect of the ice force in continuous crushing follows the same dependence as in static loadings. The frequency of observed ice forces is strongly dominated by the natural modes of the structure. Dynamically unstable natural modes tend to make the developing ice force frequencies the same as the natural frequencies. Otherwise the resulting frequency depends directly on the structural stiffness and ice velocity and inversely on the ice force range. ...

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Model Tests

SOURCE

Marcellus, R. W.; Morrison, T. B.
"Ice Design Statistics for the Canadian Beaufort Sea"
Canadian Marine Engineering Ltd.
Dome Petroleum Limited
Gulf Canada Resources Inc.
Esso Resources Canada Limited
Canadian Marine Engineering Ltd.
1982

SUMMARY

...This report is a companion report to two further CMEL reports dealing with an ice/structure interaction computer model and probabilistic ice loads on offshore structures in the Beaufort Sea. ...The intent of these reports is to collectively provide a preliminary probabilistic assessment of the global ice loads which may be applied to offshore production structures located on the Beaufort Sea Continental Shelf. These reports were initiated to demonstrate the feasibility of constructing structures to resist the ice loads in this area; they do not contain sufficient information for detailed design. ...The ice statistics contained in this report are representative of the Canadian Beaufort Sea and have been used in the computer interaction model to predict return period global ice loads on offshore production structures. ...Offshore structures ... will be subjected to interactions with large ice features. A number of interaction scenarios are possible. These involve impacts by multi-year floes, multi-year hummock low. ...This report concentrates on the larger ice features such as multi-year floes which may interact with fixed offshore structures in the region. A summary of the report is presented in Chapter 2.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Ice Design Statistics

SOURCE

Matlock, H.; Dawkins, W. P.
"Analytical Model for Ice-Structure Interaction"
Univ. of Texas, Austin
ASCE J Eng Mech Div V. 97 N. EM4 Aug. 1971
Paper 8282

SUMMARY

In an effort to predict ice-structure interaction, a simple mechanism is proposed. The structure is represented by a spring-mass system and the ice is replaced by a succession of elastic-brittle elements which impinge on the structure at a rate determined by the relative motion between the ice and the structure. A computer program is used to solve for the dynamic response of the structure. A number of test cases and variations have been solved, and the results compared with limited laboratory and field measurements.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Analytic Model

SOURCE

Metge, M.
"Ice Conditions and Ice Defense at Netserk B-44
and Adgo P-25 during the Winter of 1974-75"
Imperial Oil Limited
Calgary: Distributed by APOA, 1976
APOA Project No. 104: Measurement of Ice Pressure
on Artificial Islands - Phase I, Report No. 1

SUMMARY

During the winter of 1974-75 the ice conditions at Adgo P-25 and Netserk B-44 were periodically monitored visually to determine the interaction characteristics of the ice sheet and the islands. Most significantly the ice sheet at Netserk never became fully integral with or frozen-in to the island. Instead the ice tended to fail along a set of circumferential cracks. ...We ... call this failure mode "continuous crushing". Defense systems in the form of circumferential rows of dry and wet slots were put in place using a Ditch Witch trenching machine. ...

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Defense System

SOURCE

Michel, B.
"Ice Pressure on Engineering Structures"
U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH
June 1970

SUMMARY

One of the most important forces in the design of a dam in northern regions is the horizontal thrust applied to the structure by a solid sheet of ice. Although much progress has been made in estimating this force, there is still a long way to go before we get an accurate design value for it, mainly because of the inadequate basic knowledge of the deformation behavior of ice.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Ice Pressure

SOURCE

Michel, B.
"The Use of Model Ice to Simulate Ice Action on Offshore Structures"
Calgary: Distributed by APOA, 1972
APOA Project No. 41: Evaluation of the Mechanical Properties of
Michels Model Ice and Preliminary Ice-Structure Interaction
Experiment. Report
Contents: Pt. 1 Properties of Model Ice - Pt. 2 Model Ice
Action on Structures

SUMMARY

The most powerful tool to help solve problems of designing marine structures in ice infested waters is that of ice modeling and this report deals with the ability of an artificial material, called here model ice, to simulate real ice acting on these structures. ...It is essentially divided into two parts. In the first part a systematic study of the physical properties of interest of model ice was made, essentially by varying the proportion of the various chemicals making the material, and these properties were related to the corresponding properties of real ice. In the second part, a small exploratory model was built of five types of idealized offshore structures. A model ice sheet was formed in a basin and pushed against these structures to measure the forces and observe the movements of broken ice pieces around them. ...

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Model Ice

SOURCE

National Research Council
"Ice Pressures Against Structures"
Proceedings of a Conference held at Laval University, Quebec,
10-11 November 1966

SUMMARY

The force exerted by ice is a factor that must be taken into consideration in the design of many structures in Canada. Although the problem has been with us for many years, there is still not available to engineers the information required to predict these forces with a satisfactory degree of confidence. During the past few years, considerable knowledge and experience has been accummulated concerning the properties of ice and the forces that it can exert. The Snow and Ice Subcommitee of the National Research Council's Associate Committee on Geotechnical Research considered that it would be useful to bring this knowledge and experience together through the holding of a conference. The papers and discussions presented to the conference are contained in these proceedings.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Ice Pressure

SOURCE

Noble, P. G.; Singh, D.
"Interaction of Ice Floes with the Columns of a Semi-Submersible"
Fourteenth Annual Offshore Technology Conference, Houston, Texas,
May 3-6, 1982

SUMMARY

Semi-submersible rigs have enjoyed a history of success in oil and gas exploration world-wide. New areas of exploration are opening up in several ice infested areas, such as the Labrador Shelf, Bering Sea and the Sea of Okhotsk, and in attempts to extend drilling seasons into the ice season, work is now being carried out to investigate the ice-worthiness of semi-submersibles in the presence of pack ice.

A preliminary research project has been carried out to determine the effect of a field of small ice floes on a semi-submersible drilling unit. Physical model tests have been conducted with two main objectives; firstly, to determine the ability of the columns to prevent ice from passing between them and thus minimizing the chance of riser damage, and secondly, to determine the total ice load on the semi during interaction with ice field concentrations. Three models were used, representing one half of a four, six and eight legged semi. The dimensions and spacing of the columns were such that the heave and pitch response were kept constant. The tests were conducted at a model scale of 1:30 using synthetic ice.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Ice Floes

SOURCE

Nottingham, D.; Drage, B. T.; Christopherson, A. B.
"Ice-Resistant Structure Design: State of the Art in Alaska"
Northern Engineer, V. 14, No. 1, Spring 1982

SUMMARY

This article addresses the problems encountered by designers in arctic regions, and presents some basic hydrological criteria which must be defined for specific types of sites.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Hydrological Criteria

SOURCE

Oshima, M.; Marita, H.; Yashima, N.; Tabuchi, H.
"Model and Field Experiments for Development of Ace (Ice)
Resistant Offshore Structures"
In: 1980 Offshore Technol. Conf. Houston, Proc. Vol. IV,
Dallas, OTC, 1980, Paper OTC 3885

SUMMARY

Ice force measuring experiments have included laboratory tests, outdoor tests using medium size models in a lagoon and field tests on a large size tower specially installed in the Okhotsk Sea. Model tests of a mono-cone, mono-pod, four-legged conical structures, and four-legged conical structures, and four-legged cylindrical structures were conducted in an ice model basin. These were tested in unconsolidated and semi-consolidated first-year pressure ridges and rafted ice. Outdoor tests have been conducted at the Saroma Lagoon near Mombetsu since 1976 using medium sized models on various types of ice-resistant structures. The phenomena of vibratory crushing were also investigated. Outline of these tests including the correlation between the different tests is presented.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Model Tests

SOURCE

Pearce, J. C.; Strickland, G. E.
"Ice Forces on Conical Structures"
In: 11th Annual Offshore Technol. Conf., Houston,
1979, Proc. Vol. IV, Paper OTC 3635

SUMMARY

Since 1970 Chevron Oil Field Research Company has been operating an experimental ice force model tank to investigate ice forces on various model structures due to uniform ice sheets with various characteristics. This paper descrbes this facility and the procedures used in it to carry out determinations of ice forces on conical structures.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Model Tests

SOURCE

Ralston, T. D.
"Ice Force Design Considerations for Conical Offshore Structures"
In: POAC 77, 4th Int. Conf. Port and Ocean Eng.
under Arctic Cond., Mem. Univ. Newfoundland, St.
John's, Sept. 26-30, 1977, St. John's, Ocean Eng. Inf.
Centre, 1978, Vol. 2

SUMMARY

Analytical and model basin studies of sheet ice failure against conical structures have been previously discussed in the literature. The analytical work was based on a linear elastic description of ice deformation, with a brittle failure criterion, and was found to underestimate the model basin data. A new analysis has been developed that considers a floating ice sheet to be an elastic-plastic plate resting on an elastic-plastic foundation. The upper bound procedure of plastic limit analysis leads to a mathematical model for both sheet ice failure and rideup on a conical structure.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Mathematical Model

SOURCE

Reddy, D. V.; Cheema, P. S.; Swamidas, A. S.; Haldar, A. K.
"Stochastic Response of a Three-Dimensionl Offshore Tower to Ice Forces"
Mem. Univ. of Nfld., St. John's
Int. Symp. on Ice Probl, 3rd, Proc, Dartmouth Coll,
Hanover, NH, Aug 18-21,1975. Publ by Int. Assoc
of Hydraul Res Comm on Ice Probl, Hanover, NH 1975

SUMMARY

The probabilistic dynamic analysis of a fixed three-dimensional offshore tower presented forms part of a continuing research project on "Stochastic Analysis of Ice-Structure Interaction" which is relevant to the extensive program in Cold Regions-Oriented Ocean Engineering at Memorial University of Newfoundland. The problem of identifying the x-directional flexural modes for a three-dimensional frame was resolved by using the frame stiffness matrix (obtained for x-displacements only) for the lumped mass cantilever model. This approach implies the concept of the three-dimensional frame simulator in modeling.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Stochastic Analysis

SOURCE

Reddy, D. V.; Swamidas, A. S. J.; Cheema, P. S.
"Ice Force Response Spectrum Model Analysis of Offshore Towers"
In: Proc. Third Int. Conf. on Port and Ocean
Eng. under Arctic Conditions, Fairbanks, Univ.
Alaska, Inst. Mar. Sci., 11-15 Aug. 1975, Fairbanks,
Univ. Alaska, 1976, Vol. II, Section 9 - Structures

SUMMARY

The similarity between ice-force and earthquake records suggests the application of the well known response spectrum method in earthquake response analysis to ice-force response analysis. As far as the Author's knowledge goes this is the first time response spectra have been developed for ice forces. This study describes the use of ice-force response spectra for dynamic response analysis of framed offshore towers subjected to ice forces. The structure analazed is a fixed three-dimensional tower modelled as a planar frame. The added water mass is assumed equal to the mass of water displaced.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Spectrum Model Analysis

SOURCE

Reddy, D. V.; Cheema, P. S.; Sundararajan, C.
"Relationship Between Response Spectrum and Power Spectral
Density Analysis of Ice-Structure Interaction"
In: POAC 77, 4th Int. Conf. Port and Ocean Eng. under
Arctic Cond., Mem. Univ. Newfoundland, St. Johns,
Sept. 26-30, 1977, St. Johns, Ocean Eng. Inf. Centre,
1978, Vol. 2

SUMMARY

The mean square displacement of a structure obtained from the power spectral density function, and the maximum displacement obtained from response spectra analysis have a probabilistic relationship. These responses are determined by assuming that the given structure has properties defined in a prescribed range. The peaks of the curves, representing power spectral density functions, are broadened for a range of frequencies to account for the uncertainties of the loading and structural parameters. The work is an extension of an earlier investigation of probabilistic analysis of ice-structure interaction using and an enveloping step function power spectral density by Sundararajan and Reddy.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Spectural Analysis

SOURCE

Reddy, D. V.; Sodhi, D. S.; Arockiasamy, M.; Haldar, A. K.
"Response of an Offshore LPG Storage Platform to Simulated Ice and Wind Forces"
In: POAC 77, 4th Int. Conf. Port and Ocean Eng. under Arctic Cond., Mem. Univ Newfoundland, St. Johns, Sept. 26-30, 1977, St. Johns, Ocean Eng. Inf. Centre, 1978, Vol. 1

SUMMARY

The paper describes the dynamic response analysis to simulated ice and wind forces of a prestressed concrete floating facility for recovery, liquefaction, storage and cargo handling of liquid petroleum gas (LPG). "Three dimensional beam" and "three dimensional variable nodes isoparametric thick shell" finite elements are the two structural idealizations used. The time histories of force records (ice plus wind) are generated by superposition of a constant mean (wind + ice) and the fluctuating parts, obtained from using a nonstationary random process, filtering a shot - noise through a second order filter with postulated properties. Representing the hydrodynamic effects in terms of the added water mass concept, the structural response is obtained.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Structural Response

SOURCE

Reddy, D. V.; Arockiasamy, M.; Cheema, P. S.
"Non-Stationary Response of Offshore Towers to Ice Forces"
In: POAC 79, 5th Int. Conf. Port and Ocean Eng.
under Arctic Conditions, Norw. Inst. Technol., 1979,
Trondheim, Univ. Trondheim, 1979, Procs. Vol. II

SUMMARY

The dynamic non-stationary response analysis of a three-dimensional framed offshore tower, subjected to ice forces, is presented for single-degree-of-freedom and multi-degree-of-freedom lumped mass models, based on evolutionary coveriance matrices. The non-stationary ice force time history is idealised by an equivalent evolutionary white noise. The mean square responses are computed in the time domain using the linear (state space) formulation. The need is indicated for a study of the influence of ice force physical spectrum parameters on response.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Non Stationary Response

SOURCE

Reddy, D. V.; Muggeridge, D. B.; Swamidas, A. S. J.; Arockiasamy, M.;
Murray, J. J.; El-Tahan, H.; Hsiung, C. C.
"Dynamic Response of Moored Semisubmersible to Bergy Bit Impact, Irregular Wave, Wind, and Current Forces"
Fourteenth Annual Offshore Technology Conference, Houston, Texas, May 3-6, 1982

SUMMARY

The paper describes intitial studies on the motion and structural response of a typical semisubmersible to wind, wave, current and bergy bit impact forces. The semisubmersible is idealized as a space frame model, and the deck discretized using equivalent stiff beam elements and distributed member weights. Pierson-Moskowitz Davenport spectra are used for wave and wind forces respectively. The 100-year design criteria are based on available environmental parameters in the Hibernia region. Responses to simulated wave excitation on a 1 to 70 model, in the wave tank at Memorial University of Newfoundland, agree well with the calculated values; wind and current forces are applied as static loads in the model.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Dynamic Response Moored Semisubmersible

SOURCE

Riska, K.; Varsta, P.
"State-of-Art Review of Basic Ice Problems for a Naval Architect"
(Espoo, Finland)
Technical Research Centre of Finland
1977

SUMMARY

The structure of ice and the initial formation of ice cover are described. The occurrence and classification of ice in the Baltic are reviewed. The mechanical properties of ice, from the viewpoint of a naval architect, are examined both from theoretical and experimental standpoints. The problems of ice-going ships are studied and modeling techniques for ice-breaking and ice cover are discussed.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Naval Architect State of Art

SOURCE

Robbins, R. J.; Verity, P. H.; Taylor, T. P.; Metge, M.
"Techniques for the Study of Ice, Structure Interaction"
In: Proc. Third Int. Conf. on Port and Ocean
Eng. under Arctic Conditions, Fairbanks, Univ.
Alaska, Inst. Mar. Sci., 11-15 Aug. 1975, Fairbanks,
Univ. Alaska, 1976, Vol. II, Section 9 - Structures

SUMMARY

Design conditions for two classes of arctic offshore drilling platforms have been investigated with unique experimental techniques. A facility was designed and built to permit the evaluation of the interaction between a conical bottom founded drilling platform and moving ice sheets. A small prototype structure is positioned in a large ice test basin with a built-in towing system which moves naturally grown ice sheets past the prototype structure. The design and operation of the basin is described and a typical qualitative result of an ice/cone interaction is presented.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Design Conditions Offshore Platforms

SOURCE

Sackinger, W. M.
"Adfreeze Bonding Between Sea Ice and Offshore
Structures"
Northern Engineer, v. 9, no. 4, Winter 1977

SUMMARY

Adfreeze bonding of sea ice to Arctic offshore structures has been generally recognized as being potentially responsible for additional lateral loads on structures, loads as high as 64% above those expected due to sliding friction at the ice/structure interface. ...Recent developments in the durability of coatings for icebreaking ships have opened up the possibility of reducing the adfreeze bond strength through the use of coatings. The use of waste heat from melting the adfreeze bond has several potential problems which could lead to a need for stronger and more expensive structures. ...

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Adfreeze Bonding

SOURCE

Sackinger, W. M.; Nelson, R. D.
"Sea Ice Stresses Near Grounded Obstacles"
In: 11th Annual Offshore Technol. Conf., Houston,
1979, Proc. Vol. IV, Paper OTC 3563

SUMMARY

Stresses were measured in multi-year sea ice near a grounded floe-island. Compressive stresses as high as 250 p.s.i. were observed, in the form of impulses. A second installation in annual sea ice near a grounded pressure ridge showed tensile stress of 100 p.s.i., followed by crack formation.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Sea Ice Stresses

SOURCE

Saeki, H.; Saito, S.; Hamanka, K.; Ozaki, A.
"Experimental Study of the Compressive Strength of Sea
Ice and the Ice Forces on a Circular Pile"
Coastal Eng Jpn. V. 19 Dec. 1976

SUMMARY

Investigations are made on the testing method of strength and mechanical properties of sea ice as well as on the ice forces on an isolated circular pile. Tests show that the compressive strength of sea ice has a linear relation with the ice temperature as well as with the density of sea ice. Experiments on the ice forces on an isolated circular pile indicate that the ice forces are proportional to the thickness of sea ice and the square root of pile diameter. A proposal is made of an experimental formula on the ice forces on pile.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Experimental Study

SOURCE

Saeki, H.; Ono, I.; Ozaki, A.
"Experimental Study on Ice Forces on a Cone-Shaped and an Inclined Pile Structure"
POAC 79: The Fifth International Conference on Port and Ocean Engineering under Arctic Conditions, at the Norwegian Institute of Technology, August 13-18, 1979, proceedings V. 2

SUMMARY

...Three kinds of experiments were carried out to measure the ice forces on the sloping structures. They were the experiments on the ice forces on a cone-shaped structure and an inclined pile structure, impulsive forces on a cone-shaped structure and the coefficient of friction between the sea ice and the various materials used in offshore structures. Based on these experiments several diagrams on the ice forces exerting on a cone-shaped and an inclined pile structures and on the coefficient of friction for the various materials were proposed.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Experimental Study Cone Shaped and Inclined Pile Structure

SOURCE

Saeki, H.; Ozaki, A.
"Ice Forces on Piles"
Physics and Mechanics of Ice, Papers/International Union of
Theoretical and Applied Mechanics Symposium, Technical
University of Denmark, Copenhagen, August 6-10, 1979,
Edited by Per Tryde. New York, Springer-Verlas, 1980

SUMMARY

Investigation was made on the ice forces on an isolated vertical pile and several vertical piles which stood in a line. In order to ascertain the various effects of factors which have influence on the ice forces on piles, many kinds of experiments were carried out. The factors considered in these experiments are relative velocity between an ice floe and a pile, the sectional shape of pile, aspect ratio, and the interference among piles. Finally, it is found that the formula of the ice force on an isolated vertical pile proposed by the authors is widely applicable to the vertical pile structures.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Ice Forces on Piles

SOURCE

Semeniuk, A.
"Ice Pressure Measurements at Arnak L-30 and
Kannerk G-42"
Imperial Oil Limited
Calgary: Distributed by APOA, 1977
APOA project no. 122: In situ ice pressure measurements
1976/77 Report

SUMMARY

This report presents the results of the in situ ice pressure measurement program conducted around Imperial Oil Limited's two artificial islands, Arnak L-30 and Kannerk G-42, during the winter of 1976-77. Results consist of pressures recorded by each of the sensors, ice-to-island movement data and calculations for evaluating the net effective pressure on the island. Recommendations for improving future programs are listed.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Ice Pressure Measurement

SOURCE

Shinde, S. B.; Wards, R. D.
"Ice Rubble Field Stability"
Fourteenth Annual Offshore Technology Conference, Houston, Texas,
May 3-6, 1982

SUMMARY

Artificial islands, built as exploratory drilling platforms in the shallow waters of the southern Beaufort Sea, cause the broken ice pile-ups to form around them. These "ice rubble fields" generally form in the early winter when the ice is thin and the movements are extensive.

Previously, the sliding resistance of the ice rubble was calculated by surveying pile-up profiles and drilling through the pile-ups to obtain a keel profile. This is a tedious and expensive job. We have collected sufficient data over the past eight years to verify that the excess weight on seabed can be determined solely from aerial analysis. The sliding resistance is then calculated by using excess weight and friction factors obtained from laboratory tests.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Ice Rubble Field

SOURCE

Slomski, S.; Vivatrat, V.
"Selection of Design Ice Pressures and Application to
Impact Load Prediction"
In: POAC 83, Proc. 7th Int. Conf. on Port and Ocean Eng,
under Arctic Conditions, Helsinki, April 1983, Espoo, VTT,
1983, Vol. 2

SUMMARY

A probabilistic model is proposed to predict the relationship between the cummulative probability functions of the effective ice pressure during impact and the peak indentation pressure. The prediction is compared with existing field measurements. A Monte Carlo simulation procedure is used to combine the probabilistic ice pressure selection with the probability of occurrence of floe dimensions and velocity in a computer program for predicting the maximum annual impact load in terms of floe impact frequency. The simulation results also provide a basis for selecting design ice pressure for different loaded area sizes.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Probabilistic Model

SOURCE

Sundararajan, C.; Reddy, D. V.
"Probabilistic Analysis of Ice-Offshore Structure Interaction Using Enveloping Step Function Power Spectral Densities"
Mem Univ of Nfld., St. John's
Can J Civ Eng V. 4 N. 4 Dec. 1977

SUMMARY

A probabilistic analysis is presented for the response of offshore structures subjected to random forces due to ice floe movement. Analysis based on the averaged power spectral density of the ice force fluctuations is shown to result in unreliable designs in certain cases, owing to sensitivity to even small errors in the calculated natural frequencies of the structure. To overcome this drawback, an enveloping, step function power spectral density is proposed. A single-degree-of-freedom system and a three-dimensional offshore tower are solved as examples.

KEY WORD	**CLASSIFICATION**
Ice Structure Interaction	Probablistic Analysis

SOURCE

Tryde, P.
"Intermittent Ice Forces Acting on Inclined Wedges"
Tech Univ of Den, Lyngby
Int. Symp. on Ice Probl, 3rd, Proc, Dartmouth Coll,
Hanover, NH, Aug 18-21,1975. Publ by Int. Assoc
of Hydraul Res Comm on Ice Probl, Hanover, NH 1975

SUMMARY

A theoretical and experimental investigation of the rupture pattern in front of an inclined wedge has been performed to determine the force fluctuations during the impact of a drifting ice flow. The formulas given are based on a theoretical investigation verified by model tests with artificial and natural ice.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Ice Forces on Inclined Wedges

SOURCE

Tryde, P.
"Vertical Lifting Ice Forces Caused by a Rising Water Level, and their Action on a Vertical Slender Structure (Pile)"
Proceedings of the Second Symposium on Applied Glaciology held in New Hampshire, USA, 23-27 August, 1982 Annals of Glaciology, V. 4, 1983

SUMMARY

The problem of vertical lifting ice forces caused by a rising water level, and their action on a vertical slender structure (pile), has resting on an elastic support, in order to calculate the moments and normal forces in the sheet that cause rupture and thus produce cracks in the sheet. ...When cracks are formed, the continuous rise of the water level tends to widen them further, and the theory of elasticity is no longer valid. Usually, formation of cracks in structural members results in complete failure, but this may not be the case here. If the temperature of the air is below zero, the water penetrating the cracks will freeze when it meets with the upper part of the ice and with the air both having a temperature far below the freezing point of water. Thus the cracks will be continuously healed up, as they are widened by the rising water level. A material healing its own cracks along the rupture zone gives a completely changed stress/strain situation during the formation. This new approach may lead to a theory which is able to predict the uplift forces of ice as a function of time, of frequency and amplitude of water-level fluctuations, and of air temperature. It appears that the pile is lifted only a short distance with each cycle of water-level fluctuation. Since the downward ice force is smaller than the upward force, and the pile has a larger resistance to compression than to pulling, the pile may eventually, in the course of repeated cycles, be lifted several metres.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Vertical Lifting Forces

SOURCE

Varsta, P.; Riska, K.
"Failure Process of Ice Edge Caused by Impact with Ship's Side"
(Papers - Symposium on Ice, Ships and Winter Navigation, Oulu
University, Finland, 16-17 December, 1977. Oulu: Oulu Univ.
1977

SUMMARY

A survey of existing ice edge failure models is made, and some suggestions to improvements in these models are presented. The observed failure process of ice plate under various loading conditions is described. The process is then divided into physically different details such as crushing, shearing and bending, based on literature survey and observations made at sea. Results from tests made with fresh water beams are reported, and determination of compressive elastic constants of columnar grained fresh water ice is dealt with. (MRIS)

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Ice Edge Failure Model

SOURCE

Verity, P. H.
"Small Prototype Cone Tests, Winter 1973-74"
Imperial Oil Limited
Calgary: Distributed by APOA, 1975
APOA Project No. 65: Small Prototype Cone Test. Report

SUMMARY

A large basin was built to contain water. At one end of the basin was fixed a Small Prototype Conical Structure. This structure was a scale model of a proposed concept for offshore drilling in ice infested waters. During the winter, naturally grown ice sheets were moved against the structure by means of a towing system built into the basin. The ice was constrained to fail against the cone which was instrumented to measure the horizontal and vertical forces against it. The effects of variations in ice sheet velocity, ice thickness and ice strength on the forces encountered by the cone were investigated.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Prototype Cone Test

SOURCE

Vittorators, E. S.
"Ice Conditions around Isserk E-27, 1977/78"
Esso Resources Canada Limited
Calgary, Alta.
Beaufort E.I.S. reference work, no. RW108

SUMMARY

The ice conditions around the artificial island Isserk E-27 are described for the 1977-78 winter. The exposed geographical location of the island resulted in an extensive, elliptical rubble field (1400 by 700 m) which stabilized by the end of December. Properties of distinct features such as rubble field, rubble field-ice sheet interface ("active zone"), and cracks were studied. Using surveying techniques, it was concluded that the rubble field behaved as a solid annulus attached to the island during the period Feb. 20 - May 12 when the surrounding ice sheet movement was limited to less than 2 m. Profiles through the active zone revealed both crushing and bending failure mechanisms. The existence of a preferred crystallographic orientation of the sea ice was confirmed by the Mackenzie Delta; it was also inferred that the presence of offshore structures such as artificial islands, influences the ice crystallography near the structure. The mathematical formalism for relating environmental forces to the ice force felt by an artificial island is outlined and it is applied to calculations relating to the safety of Isserk.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Artificial Island-Ice Conditions

SOURCE

Vivatrat, V.
"Strains and Strain Rates in Sea Ice Indentation"
Fourteenth Annual Offshore Technology Conference,
Houston, Texas, May 3-6, 1982

SUMMARY

This paper is concerned with the prediction of deformation pattern, strains and strain-rates in sea ice indentation problems and their application to ice load prediction.

The paper discusses the applicability of the rigid-plastic assumption in sea ice indentation and presents a procedure for estimating deformation, strains, and strain-rates from the velocity fields which are constructed for the purpose of estimating the maximum indentation pressure. Results are given for the case of plane, steady state indentation. A procedure for estimating the stress field around the indenter from these results is outlined and its limitations discussed.

The paper also discusses the development of indentation pressure with deformation as well as the similarity between test results and cavity expansion solutions.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Strains and Strain Rates

SOURCE

Zabilansky, L. J.; Nevel, D. E.; Haynes, F. D.
"Ice Forces on Simulated Structures"
US Army Cold Reg Res & Eng Lab, Hanover, NH
Int. Symp. on Ice Probl, 3rd, Proc, Dartmouth Coll,
Hanover, NH, Aug 18-21,1975. Publ by Int. Assoc
of Hydraul Res Comm on Ice Probl, Hanover, NH 1975

SUMMARY

Simulated structures mounted on a portable apparatus were used to investigate ice forces on marine strutures. Various geometric shapes of simulated structures or piles were pushed against natural lake ice. Parameters varied were size, shape, pile velocity, friction, initial pile-ice contact and slope of the pile.

KEY WORD	CLASSIFICATION
Ice Structure Interaction	Simulated Structures

ICE TECHNOLOGY

1.3 ICE STRUCTURE INTERACTION, MOVING VESSELS

LIST OF TECHNICAL PUBLICATIONS

ICE TECHNOLOGY - ICE-STRUCTURE INTERACTION, MOVING VESSELS

Title	Author	Publication	Publication Date	Page No.
Problems in Ice Engineering	Assur, A.	USA Cold Reg Res & Eng Lab, Hanover, NH, Int Symp on Ice Probl, 3rd, Proc, Dartmouth Coll, Hanover, NH, Aug 18-21 1975 Publ. by Int Assoc of Hydraul Res Comm on Ice Probl, Hanover, NH	1975	147
Bibliography of Ice Properties and Forecasting Related to Transportation in Ice-Covered Waters	Greisman, P. E.	U.S. Coast Guard, Office of Research and Development Springfield, Virginia Distributed by NTIS	1980	148
Icebreakers and Icebreaking (Citations from the NITS Data Base)	Habercom, G. E., Jr.	NTIS, Springfield, VA Publ. by NTIS	1978	149
Glaciological Research Relevant to the Construction of Ice-Going Ships	Kohnen, H.	Ocean Engineering, v. 3	1976	150
Linear Elements of Sea-Ice Relief	Kupetskii, V. N.	(Polar Geography, v. 3, no. 2, Apr-June 1979) (Izvestiia - Vsesoiuznoe Geograficheskoe Obshchestvo, v. 109, no. 1) Bibliography		151
Arctic Terminal for Icebreaking Tankers Study Conceptual Design	Lewis, A. E.	Tankers Study Conceptual Design	1979	152
State-of-Art Review of Basic Ice Problems for a Naval Architect	Riska, K. Varsta, P.	(Espoo, Finland) Technical Research Centre of Finland	1977	153

LIST OF TECHNICAL PUBLICATIONS

ICE TECHNOLOGY - ICE-STRUCTURE INTERACTION, MOVING VESSELS

Title	Author	Publication	Publication Date	Page No.
Marine Structures and Ships in Ice	Report: River & Harbour Laboratory	P.O. Box 300 N-1322 Hdvik, Norway	1980	154
Effect of Physicomechanical Properties and Uneven Thickness of Ice on the Motion of Ships in the Autumn-Winter Season	Smirnov, V. I.	(Problems of the Arctic and the Antarctic, v. 46, 1975 Translation of: Vliianie fiziko-mekhanicheskikh svoistv i neravnomernosti tolshchin l'da na dvizhenie sudov v osenne-zimnii period	1976	155
Failure Process of Ice Edge Caused by Impact with Ship's Side	Varsta, P. Riska, K.	(Papers - Symposium on Ice, Ships and Winter Navigation, Oulu University, Finland, 16-17 December, 1977. Oulu: Oulu Univ.	1977	156

SOURCE

Assur, A.
"Problems in Ice Engineering"
USA Cold Reg Res & Eng Lab, Hanover, NH
Int Symp on Ice Probl, 3rd, Proc, Dartmouth Coll,
Hanover, NH, Aug 18-21 1975
Publ. by Int Assoc of Hydraul Res Comm on Ice Probl,
Hanover, NH 1975

SUMMARY

The design of large structures in ice infested water such as piers, offshore terminals and platforms is subject to considerable uncertainties due to lack of suitable data and experience. Observations on ships provide clues for some of the most serious problems to be solved. This paper discusses the effect of friction, adfreezing, side pressure and forces on random ice agglomerations. Horizontal ice pressures can stop ships, so "ice pillows" under moderate ice conditions.

KEY WORDS	CLASSIFICATION
Ice-Structure Interaction	Moving Vessels

SOURCE

Greisman, P. E.
"Bibliography of Ice Properties and Forecasting Related to
Transportation in Ice-Covered Waters"
U.S. Coast Guard, Office of Research and Development
Springfield, Virginia
Distributed by NTIS. 1980

SUMMARY

This bibliography is intended as a tool for those performing research in ice properties related to ships, particularly icebreaker operations. The areas covered are the properties of lake, sea and river ice as they relate to mechanical behavior, remote sensing, and ice motions. Other topics included are: ice climatology, pressure ridges, shipping routes, vehicles and vessels, scientific studies by the Arctic Ice Dynamics Joint Experiment (AIDJEX) and other bibliographies.

KEY WORDS	CLASSIFICATION
Ice-Structure Interaction	Moving Vessels

SOURCE

Habercom, G. E., Jr.
"Icebreakers and Icebreaking (Citations from the NITS Data Base)"
NTIS, Springfield, VA
Publ. by NTIS
Dec. 1978

SUMMARY

The design and performance of icebreakers, ice breaking, ice navigation and ice distribution are reviewed in these Government-sponsored research reports. This updated bibliography was prepared by searching the 1964-November 1978 data base of NTIS. It contains 213 abstracts, 10 of which are new entries to the previous edition.

KEY WORDS	CLASSIFICATION
Ice-Structure Interaction	Moving Vessels

SOURCE

Kohnen, H.
"Glaciological Research Relevant to the Construction of Ice-Going Ships"
Ocean Engineering, v. 3
1976

SUMMARY

The transportation of rich mineral resources from the Arctic by means of large ice-going bulk and oil carrier, is expected to be a suitable and economical technique. The construction of such large vessels requires the knowledge of various glaciological parameters of the sea ice and their dependence on Arctic environmental conditions, of particular interest on the small scale are the strength, elasticity, and metal to ice friction characteristics, on a larger geophysical scale relevant parameters are the ice stress, pressure, and movement rates and the relation of these parameters to the temperature and salinity of the ice and to the wind field and the ocean current. Furthermore electrical and electromagnetical properties of the ice are relevant to the navigation in ice covered waters by the aid of remote sensing techniques. The German shipyard A.G. Weser in Breman initiated in 1972 an expedition to the Canadian Arctic to study all relevant physical properties at one location and at the same time to comprehend the whole glaciological regime. The expedition was a cooperative effort between Brock University, St. Catharines (Canada) and the University of Munster (W. Germany). The field measurements were carried out in May and June 1972 on the sea ice between Pond Inlet (Northern Baffin Island) and Bylot Island, N.W.T. This article summarizes the essential results and presents a synthesis of all the results.

KEY WORDS	CLASSIFICATION
Ice-Structure Interaction	Moving Vessels

SOURCE

Kupetskii, V. N.
"Linear Elements of Sea-Ice Relief"
(Polar Geography, v. 3, no. 2, Apr-June 1979)
(Izvestiia - Vsesoiuznoe Geograficheskoe Obshchestvo, v. 109, no. 1)
Bibliography

SUMMARY

The empirical evidence suggests that all types of ice display linear elements that (sic) can be compared with lineaments in the earth's surface. The basic global jointing patterns of NE-SW and NW-SE appears to extend to sea ice, and ice-navigation experience suggests that movement is easier along these courses while courses close to the N-S and E-W directions result more frequently in ships becoming icebound. Closer study of ice jointing patterns may thus offer new prospects for ice nagivation, especially in connection with the establishment of new high-latitude icebreaker routes.

KEY WORD	CLASSIFICATION
Ice-Structure Interaction	Moving Vessels

SOURCE

Lewis, A. E.
"Arctic Terminal for Icebreaking Tankers Study Conceptual Design"
March 1979

SUMMARY

Administration; Alaska; Arctic climate; Arctic Ocean; Business operation; capacity; Chukchi Sea; climate; cost; crude oil; design; economic factor; engineering; English; government; ice; ice breaker; management; marine transportation; meteorological phenomenon; mooring; North America; offshore; offshore structure; offshore terminal; offshore well; petroleum; physical property; pipeline; pipelining, ship and storage; planning; report; seas and oceans; ship; storage capacity; storage facility; system (assemblage); tanker; transportation; transportation system; transportation terminal; United States; transportation terminal; United States; water; well.

KEY WORD	CLASSIFICATION
Ice-Structure Interaction	Moving Vessels

SOURCE

Riska, K.; Varsta, P.
"State-of-Art Review of Basic Ice Problems for a Naval Architect"
(Espoo, Finland)
Technical Research Centre of Finland
1977

SUMMARY

The structure of ice and the initial formation of ice cover are described. The occurrence and classification of ice in the Baltic are reviewed. The mechanical properties of ice, from the viewpoint of a naval architect, are examined both from theoretical and experimental standpoints. The problems of ice-going ships are studied and modeling techniques for ice-breaking and ice cover are discussed.

KEY WORD	CLASSIFICATION
Ice-Structure Interaction	Moving Vessels

SOURCE

"Marine Structures and Ships in Ice"
Performing Org: norske Veritas Research Division;
River and Harbor Laboratory P.O. Box 300 N-1322 Hovik Norway
Klaebuveien 153 7034 Trondheim NTH Norway
Subfile: MRIS
Project Start Date: 1978
Project Termination Data: 1980

SUMMARY

Purpose: To develop computational methods and experimental techniques to predict the ice loads on ships and marine structures intended for arctic and subarctic waters. To acquire information about ice characteristics and environmental conditions in these areas. Benefits: The project is expected to provide adequate information about laods and environmental conditions in connection with design and evaluation of the safety of structures exposed. Activities: The following theoretical and experimental studies will be carried out: Collection of ice and environmental data for the Arctic. Evaluation of the mechanical properties of ice during short and long term load cycles. Investigation of local and global ice loads on ships and marine structures. Prediction of the resistance of ships in level ice. Study of loads on screws and rudder during interaction with ice. Investigation of ice-induced structural vibration. Evaluation of facilities (mechanical and pneumatic devices) in order to reduce the resistance and loads in ice. Survey of possible transport, terminal and offshore loading systems for arctic conditions. Development of ice modelling techniques. Model testing of ships and different offshore structures for prediction of loads and resistance in level ice and ridges. Investigation of the physical nature of icing and means to reduce the rate of icing. Evaluation of "optimum" form (shape) of structures in order to minimize the loads and resistance in ice. Design case, for illustration of the use of available methods and information provided through MSSI. At the end of 1980 an Ice Seminar will be held where the work and results of the MSSI project will be presented. Marine Structures and Ships in Ice (MSSI) is a joint research project sponsored by Scandinavian industry and institutions.

KEY WORD	CLASSIFICATION
Ice-Structure Interaction	Moving Vessels

SOURCE

Smirnov, V. I.
"Effect of Physicomechanical Properties and Uneven Thickness of Ice on
the Motion of Ships in the Autumn-Winter Season"
(Problems of the Arctic and the Antarctic, v. 46, 1975
Translation of: Vliianie fiziko-mekhanicheskikh svoistv i
neravnomernosti tolshchin l'da na dvizhenie sudov v osenne-
zimnii period

SUMMARY

... On the basis of the results obtained it can be tentatively concluded that for strong consolidated winter pack ice 40-100 cm thick a change in the unevenness of distribution of ice thickness from 0 to 1-2 points does not substantially affect the speed of powerful icebreakers. Consequently, for standard deviations of ice thicknesses up to +-0.10 - 0.15 m, for ratios of the greatest to the smallest thicknesses up to 1.4 and for hummocking of ice of less than 2 points a consolidated pack ice cover can be considered relatively level for navigational purposes. With any incease in the uneveness of distribution of ice thickness, for every point above 2 the speed of the icebreaker decreases by 15-35% ...

KEY WORD	CLASSIFICATION
Ice-Structure Interaction	Moving Vessels

SOURCE

Varsta, P.; Riska, K.
"Failure Process of Ice Edge Caused by Impact with Ship's Side"
(Papers - Symposium on Ice, Ships and Winter Navigation, Oulu
University, Finland, 16-17 December, 1977. Oulu: Oulu Univ.
1977

SUMMARY

A survey of existing ice edge failure models is made, and some suggestions to improvements in these models are presented. The observed failure process of ice plate under various loading conditions is described. The process is then divided into physically different details such as crushing, shearing and bending, based on literature survey and observations made at sea. Results from tests made with fresh water beams are reported, and determination of compressive elastic constants of columnar grained fresh water ice is dealt with. (MRIS)

KEY WORD	CLASSIFICATION
Ice-Structure Interaction	Moving Vessels

ICE TECHNOLOGY

1.4 ICE SCOUR

LIST OF TECHNICAL PUBLICATIONS

ICE SCOUR

Title	Author	Publication	Publication Date	Page No.
Iceberg Incursion Probabilities into Subsea Structures	Benedict, C. P. Lewis, J. C.	Presented at Offshore Tech. Conf.	1973	157
Estimates of Iceberg Scour Depths	Chari, T. R. Peters, G.R.	Proceedings of the Symp. on Production and Transportation Systems for the Hibernia Discovery, St. John's Nfld	1981	158
An Analytical Study of Ice Scours on the Sea Bottom	Fenco Consultants Limited	Report to Arctic Pet. Operators Assoc., Project No. 69-1	1975	159
Ice-Scoured Topography and its Relationships to Bedrock Structure and Ice Movement in Parts of Northern Scotland and West Greenland	Gordon, J. E.	Geografiska Annaler. Series A: Physical Geography, V. 63A, No. 1-2,	1981	160
Iceberg Scouring and Pipeline Burial Depths	Green, H. P. Reddy, A. S. Chari, T. R.			161
Submarine Pipeline Crossing of M'Clure Strait	Kaustinen, O. M. Brown, R. J. Palmer, A. C.			162
Mathematical Analysis of Ice Scour	Kivisild, H. R. Pilkington, G. R. Iyer, S. H.	Reprint, ASME Energy Sources Technology Conference, Houston, Texas	1981	163

LIST OF TECHNICAL PUBLICATIONS

ICE SCOUR

Title	Author	Publication	Publication Date	Page No.
Ice Scour Studies on the Labrador Shelf	Lewis, C. F. M. Barrie, J. V.	Offshore Region, Goose Bay, Labrador, September 4-6, 1980, Newfoundland Institute for Cold Ocean Science, St. John's: Memorial University of Newfoundland,	1980	164
Soil Stabilization for Protection of Sea-Bed Structures from Ice Scour	Morgenstern, N. R. Sterne, K.	Edmonton: Boreal Institute for Northern Studies	1980	165
Use of Mathematical Models to Estimate Ice Scour	Pilkington, G. R.			166
Arctic Continental Shelf Processes and Morphology Related to Sea Ice	Reimnitz, E. Toimil, L. J. Barnes, P. W.	Zonation, Beaufort Sea, Alaska AIDJEX Bulletin No. 36, May	1977	167
High Rates of Bedload Transport Measured from Infilling Rate of Large Strudel-scour Craters in the Beaufort Sea, Alaska	Reimnitz, E. Kempema, E. W.			168
Ice Scour Tracks on the Beaufort Sea Continental Shelf -- Their Form and Interpretation of their Processes Creating Them	Wahlgren, R. V.	Ottawa, Ont., National Library of Canada, M.A. Thesis, Carleton University, Department of Geography, Jan. 1979	1979	169

SOURCE

Benedict, C. P.; Lewis, J. C.
"Iceberg Incursion Probabilities into Subsea Structures"

SUMMARY

This paper presents a method for describing analytically the distribution of iceberg drafts at a particular latitude and of combining this with site bathymetry and iceberg flux data to calculate incursion probabilities and mean times between incursions as a function of site design parameters.

KEY WORD	CLASSIFICATION
Ice Scour	Iceberg Incursion

SOURCE

Chari, T. R.; Peters, G. R.
"Estimates of Iceberg Scour Depths"
Memorial University of Newfoundland, St. John's, Newfoundland, Canada

SUMMARY

The maximum depth of iceberg scour at any location can be estimated using the basic concepts of Geotechnical engineering and the principle of energy balance. The water depth will, to a large extent, control the magnitude of the scour problem by limiting the size of the berg likely to ground. The shape of the iceberg keel, the type of the seabed sediment and the coefficient of hydrodynamic drag between the iceberg and ocean currents are the major factors influencing the scour size.

KEY WORD	CLASSIFICATION
Ice Scour	Estimates of Scour Depth

SOURCE

Fenco Consultants Limited
"An Analytical Study of Ice Scour on the Sea Bottom"
Calgary: Distributed by APOA, 1975
APOA Project No. 69: An Analytical Study of Ice Scour, Report

SUMMARY

... The study covers all aspects of scouring: a review of literature; environmental factors required for study; types of ice formations; marine sediments; plus several idealistic mathematical models to predict scour for different situations. In particular, a dynamical model has been developed (by solving the basic equations of motion of a body being driven into a sloping sea bed) and the solutions compared with other simpler model solutions which use either energy conservation or static equilibrium conditions. Finally, suggestions for model tests are given which could be used to verify the mathematical solutions presented here. ...

KEY WORD	CLASSIFICATION
Ice Scour	Review of Literature and Mathematical Models

SOURCE

Gordon, J. E.
"Ice-Scoured Topography and its Relationships to Bedrock Structure
and Ice Movement in Parts of Northern Scotland and West Greenland"
Geografiska Annaler. Series A: Physical Geography, V. 63A, No. 1-2, 1981

SUMMARY

The topographic form of areal scouring relates closely to bedrock structure, in particular to the strike and dip of bedding planes, layering, joints and other lines of structural weakness. Asymmetric 'rouche moutonnee' - type forms generally exist in sympathy with bedrock structure regardless of ice movement direction. Locally in massive bedrock of suitable surface geometry they may reflect glacier-induced fracturing alone. The forms of ice-scoured topography have important implications concerning glacier bed models.

KEY WORD	CLASSIFICATION
Ice Scour	Ice-Scoured Topography

SOURCE

Green, H. P.; Reddy, A. S.; Chari, T. R.
"Iceberg Scouring and Pipeline Burial Depths"

SUMMARY

Seabed disturbance due to ploughing by iceberg keels is a recognized phenomenon which threatens offshore operations along the Eastern Canadian Continental Shelf. This threat to seafloor installations such as well heads, pipelines and foundations is a factor to be taken into account in the design of production systems. Determining the maximum depth of scour is difficult due to the many variables including iceberg size, stability, driving forces and the geotechnical properties of the seabed. This paper considers the geotechnical aspects of the problem and the evaluation of the seabed resistance to displacement due to ice contact.

Earlier papers by the authors simplified iceberg shape as a rectangular block with a vertical face. Here the effects of front face shape are examined. Two theoretical approaches to soil resistance, the method of trial wedges and the method of characteristics are compared with experimental results. Another phenomenon of importance during the scour process is the mass disturbance of the soil below the scour. Tests were conducted with an instrumented pipeline model to investigate the effect of iceberg model front face inclinations on soil pressures generated below the scour zone. The implications of the result in determining the safe burial depths are discussed.

KEY WORD	CLASSIFICATION
Ice Scour	Scouring and Pipeline Burial Depth.

SOURCE

Kaustinen, O. M.; Brown, R. J.; Palmer, A. C.
"Submarine Pipeline Crossing of M'Clure Strait"

SUMMARY

This paper describes the design and preferred construction technique for a large-diameter pipeline crossing of a wide and deep strait in the Arctic Islands. Construction is by ice-hole bottom pull, and connections are made by one-atmosphere welding.

KEY WORD	CLASSIFICATION
Ice Scour	Submarine Pipeline

SOURCE

Kivisild, H. R.; Pilkington, G. R.; Iyer, S. H.
"Mathematical Analysis of Ice Scour"

SUMMARY

To study scour of sea bottom by ice features, mathematical models have been developed.

The model of general validity for solid ice masses is a dynamic model. This model has been developed by solving the basic equations of motion of a body driven into a sloping seabed.

The model indicates that under steady horizontal forces the ice form does not lift significantly on scouring. This permits development of a simpler mathematical model for iceberg grounding, using energy conservation.

Another simplified model uses static equilibrium conditions and calculates the path of least resistance or minimum work done by an ice mass moving into shallow water.

Essentially, significant scouring is indicated if the keels of icebergs are narrow or if the iceberg is pushed by solid pack ice.

Different models are required for unconsolidated ridges and these are based on unravelling of accumulated ice rubble.

KEY WORD	CLASSIFICATION
Ice Scour	Mathematical Analysis

SOURCE

Lewis, C. F. M.; Barrie, J. V.
"Ice Scour Studies on the Labrador Shelf"
Offshore Region, Goose Bay, Labrador, September 4-6, 1980
Newfoundland Institute for Cold Ocean Science,
St. John's: Memorial University of Newfoundland, 1980

SUMMARY

Numerous furrows in unconsolidated surficial deposits have been revealed by side scan sonar transects during geological reconnaissance of the Labrador Shelf by the Atlantic Geoscience Centre over the last decade. The furrows, tens of metres wide, are generally attributed to sediment gouging by bottom-dragging icebergs and represent a menace to potential offshore wellheads and pipelines. Three types of study are currently in progress to clarify the nature of this scouring process. 1. Regional Distribution of Ice-Scour Features ... 2. Site Investigation and Time Series Mapping (and) 3. Modern Iceberg Grounding Dynamics...

KEY WORD	CLASSIFICATION
Ice Scour	Studies on the Labrador Shelf

SOURCE

Morgenstern, N. R.; Sterne, K.
"Soil Stabilization for Protection of Sea-Bed
Structures from Ice Scour"
Edmonton: Boreal Institute for Northern Studies, 1980

SUMMARY

One of the major problems to be considered in the design of pipelines and drilling platforms in the Beaufort Sea is the damage that can result from ice scouring. ...It was thus decided to conduct a laboratory investigation to determine whether the sea bed in the vicinity of such structures could be stabilized by in-situ mixing of the sea bed sediments with cement to a degree sufficient to offer substantial resistance to ice forces. ...The preliminary laboratory work that was carried out is described in this report. In addition, problems of ice scouring and the formation of pressure ridges were reviewed from the available literature. Finally, the results of the laboratory work are discussed and proposals for further research outlined. ...

KEY WORD	CLASSIFICATION
Ice Scour	Laboratory Investigation for Protection

SOURCE

Pilkington, R.
"Use of Mathematical Models to Estimate Ice Scour"

SUMMARY

Two basic methods are available to estimate ice scour on natural oceanbeds:

1) Statistics derived from scour records, and
2) Scour depths estimated from physics of ice/water/soil interaction.

On natural oceanbeds, scour marks have shown to provide reasonable basis for the estimating of scour with a given frequency in a given location. The methods to apply survey records to estimate scour depths with various risks are discussed in the presentation by Dr. Roger Pilkington.

A good mathematical model will give input for distribution functions in this type of analysis.

Mathematical models are needed if the bed is reformed by either reshaping it or by trenching and filling wide areas, since scour depths may be different from natural scour. Even more drastic deviations will occur if man-made obstacles are placed in the way of scouring ice masses. The problem is complex but a general dynamic model has been established for ice masses including icebergs, and various soil interaction theories have been applied. Different mathematical models are required for unconsolidated ridges. These are based on unravelling of accumulated ice rubble.

Mathematical models of ice scour have provided a useful tool and have been used since 1969.

KEY WORD	CLASSIFICATION
Ice Scour	Estimating Ice Scours

SOURCE

Reimnitz, E.; Toimil, L. J.; Barnes, P. W.
"Arctic Continental Shelf Processes and Morphology Related
to Sea Ice Zonation, Beaufort Sea, Alaska"
AIDJEX Bulletin No. 36, May 1977

SUMMARY

Landsat-1 and NOAA satellite images for winter 1972-73 and ice seafloor data from several sources were used to study sea ice zonation and dynamics and their relation to bottom morphology and geology on the Beaufort Sea continental shelf of arctic Alaska. ...A casual relation is seen between the spatial distribution of major ice ridge systems and offshore shoals downdrift of major coastal promontories. ...There is evidence that anomalies in the overall arctic shelf profile are related to sea ice zonation, ice dynamics, and bottom processes. The ice zonation proposed - (a) bottom-fast ice, (b) floating fast ice, (c) stamukhi, and (d) seasonal pack ice - emphasizes ice interaction with the shelf surface and differs from previous zonation. Certain aspects of the results reported here are directly applicable to planned offshore developments in the Prudhoe Bay oil field. ...

KEY WORD	CLASSIFICATION
Ice Scour	Relating Satellite Images and Sea Floor Data

SOURCE

Reimnitz, E.; Kempema, E. W.
"High Rates of Bedload Transport Measured from Infilling Rate of Large Strudel-scour craters in the Beaufort Sea, Alaska"

SUMMARY

Strudel scours are craters as much as 20 m wide and 4 m deep, that are excavated by vertical drainage flow during the yearly spring flooding of vast reaches of fast ice surrounding arctic deltas; they form at a rate of about 2.5 $km^{-2}yr^{-1}$. Monitoring two such craters in the Beaufort Sea, we found that in relatively unprotected sites they fill in by deposition from bedload in 2 to 3 years. Net westward sediment transport results in sand layers dipping at the angle of repose westward into the strudel-scour crater, whereas the west wall of the crater remains steep to vertical. Initially the crater traps almost all bedload: sand, pebbles, and organic detritus; as infilling progresses, the materials are increasingly winnowed, and bypassing must occur. Over a 20-m-wide sector, an exposed strudel scour trapped 360 m^3 of bedload during two seasons; this infilling represents a bedload transport rate of 9 $m^3yr^{-1}m^{-1}$. This rate should be applicable to a 4.5-km-wide zone with equal exposure and similar or shallower depth. Within this zone, the transport rate is 40,500 m^3yr^{-1}, similar to estimated longshore transport rates on local barrier beaches. On the basis of the established rate of cut and fill, all the delta-front deposits should consist of strudel-scour fill. Vibracores typically show dipping interbedded sand and lenses of organic material draped over very steep erosional contacts, and an absence of horizontal continuity of strata--criteria that should uniquely identify high-latitude deltaic deposits. Given a 2- to 3-year lifespan, most strudel scours seen in surveys must be old. The same holds true for ice gouges and other depressions not adjusted to summer waves and currents, although these features record events of only the past few years. In view of such high rates of bottom reworking of the shallow shelf, any human activities creating turbidity, such as dredging, would have little effect on the environment. However, huge amounts of transitory material trapped by long causeways planned for offshore development would result in major changes in the environment.

KEY WORK	CLASSIFICATION
Ice Scour	Scour Craters in the Beaufort Sea, Alaska

SOURCE

Wahlgren, R. V.
"Ice-Scour Tracks on the Beaufort Sea Continental Shelf"
Ottawa: National Library of Canada, 1979
Thesis (M.A.) - Carleton University, Ottawa, 1979

SUMMARY

Quantitative geomorphological analysis are made of ice-scour tracks created by drift ice scraping the seabed of the southeastern Beaufort Sea. The data consists of measurements from echograms and sonograph mosaics. ...The results ... include: grounding ice having less than 45 m draft usually does not dig further into the sediment as the ice keel proceeds upslope; keels approaching normal to the slope leave shorter tracks than keels which travel along the slope; ice floe interaction processes can explain the various planimetric forms of tracks; deep ice keel drafts and tracks are fairly rare events; and excess pore water pressure beneath a moving, grounded ice keel evidently can support negative buoyancy of the keel. The ice-scouring process is analysed using an energy flow model which is adaptable to computer simulation.

KEY WORD	CLASSIFICATION
Ice Scour	Geomorphological Analysis of Ice-Scour Tracks

2.0 ARCTIC GEOTECHNIQUE

LIST OF TECHNICAL PUBLICATIONS

ARCTIC GEOTECHNIQUE

Title	Author	Publication	Publication Date	Page No.
Western Arctic Moderate Draft Harbour	Advisory Committee on Northern Development	Transportation Committee Steering Group on Marine Transportation	1977	170
Geotechnical Engineering for Cold Regions	Andersland, O.B./ Anderson, D.M.	McGraw-Hill, New York, N.Y., 566p.	1978	171
Physics, Chemistry, and Mechanics of Frozen Ground: A Review	Anderson, D.M./ Morgenstern, N.R.	Proceedings 2nd Int. Conf. on Permafrost, North American Contribution, Yakutsk, U.S.S.R., National Academy of Sciences, Washington, D.C., pp 257-288	1973	172
Subsea Cryolithozone of the Arctic Ocean	Are, F.E.	U.S. Army CRREL, Draft Translation 686, Hanover N.H., 26p.	1978	173
Transportation, Preparation and Storage of Frozen Soil Samples for Laboratory Testing	Baker, T.H.W.	ASTM, Spec. Tech. Publ. 599, pp 88-112.	1976	174
Penetration Tests in Subsea Permafrost, Prudhoe Bay, Alaska	Blouin, S.E./ Chamberlain, E.J./ Sellman, P.V./ Garfield, D.E.	U.S. Army, CRREL, Rpt. 79-7, Hanover, N.H., 45p.	1979	175
Permafrost in Canada: Its Influence on Northern Development	Brown, R.J.E.	University of Toronto Press, Toronto, 234p.	1970	176
Permafrost Terminology	Brown, R.J.E./Kupsch, W.O.	National Research Council, Canada, Associate Committee Geotechnical Research, Tech. Memo 111, 62p.	1974	177

LIST OF TECHNICAL PUBLICATIONS

ARCTIC GEOTECHNIQUE

Title	Author	Publication	Publication Date	Page No.
Distribution of Permafrost in North America and its Relationship to the Environment: 1963-1973	Brown, R.J.E./Pewe, T.L.	Proceedings of 2nd Int. Conf. on Permafrost, North America Contribution, Yakutsk, U.S.S.R., National Academy of Sciences, Washington, D.C. pp 71-100.	1973	178
Canadian Foundation Engineering Manual	Canadian Geotechnical Society	Canadian Geotechnical Society, Montreal, Quebec, Canada	1978	179
Engineering Properties of Subsea Permafrost in the Prudhoe Region of the Beaufort Sea	Chamberlain, E.J./ Sellmann, P.V./Blouin, S.E./Hopkins, D.M./ Lewellen, R.I.	Proceedings of 3rd Int. Conf. on Permafrost, Edmonton, Alberta, Canada, National Research Council of Canada, Ottawa, pp 629-635	1978	180
Site Investigations and Submarine Soil Mechanics in Polar Regions	Chamberlain, E.J.	U.S. Army, CRREL, Spec. Rpt. 81-24, Hanover, N.H., 18p.	1981	181
Cold Regions Engineered Earthworks	Clark, J.I., Shields, D.H. Graham, J. Rymes, J.E.	Transportation Development Centre, Report No. TP4424E	1983	182
Sheet Pile Structures	Cornfield, G.M.	in Foundation Engineering Handbook, H.F. Winterkorn & H.Y. Fang, editors, Van Nostrand Reinhold Co., Toronto, Ontario, Canada, pp 418-444.	1975	183
Use of Thermal Piles for Offshore Frozen Embankments	Davison, B.E./Rooney, J.W.	Proc. 4th Int. Conf. on Port and Ocean Engineering Under Arctic Conditions, 1977, vol. 1, Ocean Engineering Info Centre, Memorial University, St. John's, Nfld., pp 358-369.	1978	184

LIST OF TECHNICAL PUBLICATIONS

ARCTIC GEOTECHNIQUE

Title	Author	Publication	Publication Date	Page No.
Cellular Structures and Braced Excavations	Dismuke, T.D.	in Foundation Engineering Handbook, H.F. Winterkorn & H.Y. Fang, editors, Van Nostrand Reinhold Co., Toronto Ontario, Canada, pp 445-480.	1975	185
Hershel Island, Feasibility of a Marine Terminal	Department of Public Works	Report, Ottawa, 141p.	1970	186
Creep Behavior of Frozen Saline Silt Under Isotropic Compression	Domaschuk, L./Marr, C.S./Shields, D.H./ Yong, E.	Proceedings 4th Int. Conf. on Permafrost, Fairbanks, AK, National Academy Press, Washington, D.C. pp 238-243	1983	187
Geology and Economic Minerals of Canada	Douglas, R.J.W.	Economic Geology Report No. 1, Queen's Printer for Canada, Geological Survey of Canada, Ottawa 838p.	1970	188
Design and Installation of Pile Foundations and Cellular Structures	Fang, H.Y./Dismuke, T.D. ed.	Proceedings of Conference on Design and Installation of Pile Foundations and Cellular Structures, ENVO Publishing Co., Inc., Lehigh Valley, Penn., U.S.A., 447p.	1970	189
Site Evaluation for Artificial Drilling Island in the Beaufort Sea	Hailey, D.W.	1st Canadian Conference on Marine Geotechnical Engineering, Calgary, Alberta, Canada.	1979	190
Engineering Applications of New Probabilistic Seismic Ground-Motion Maps of Canada	Heidebrecht, A.C./ Basham, P.W./Rainer, J.H./Berry, M.J.	Can. J. Civ. Eng. 10, Dec., pp 670-680.	1983	191

LIST OF TECHNICAL PUBLICATIONS

ARCTIC GEOTECHNIQUE

Title	Author	Publication	Publication Date	Page No.
Geotechnical Aspects in an Arctic Wharf Design	Holubec, I./McDonald, A.F.	Preprints, 33rd Can. Geot. Conf., Calgary, Alberta, Canada.	1980	192
Resonant Driving in Permafrost	Huck, R.W./Hull, J.R.	Foundation Facts, vol. 7, No. 1, pp 11-15	1971	193
The Occurence of Permafrost and Frozen Sub-seabottom Materials in the Southern Beaufort Sea	Hunter, J.A./Judge, A.S./MacAuley, H.A./Good, R.L./Gagne, R.M./Burns, R.A.	Environment Canada, Beaufort Sea Project, Tech. Rpt. 22, Victoria, B.C., 174p.	1976	194
Chemistry of Interstitial Water from the Subsea Permafrost, Prudhoe Bay, Alaska	Iskandar, I.K./Osterkamp, T.E./Harrison, W.D.	Proceedings of 3rd Int. Conf. on Permafrost, Edmonton, Alberta, Canada, National Research Council of Canada, Ottawa, pp 92-98.	1978	195
Permafrost Engineering Design and Construction	Johnston, G.H.	Associate Committee on Geotechnical Research, National Research Council of Canada, John Wiley and Sons, Toronto, 540p.	1981	196
Use of the Static Penetration Test in Frozen Soils	Ladanyi, B.	Canadian Geotechnical Journal, Vol. 13, No. 2, pp 95-110.	1976	197
Evaluation of In-situ Creep Properties of Frozen Soils with the Pressuremeter	Ladanyi, B./Johnston, G.H.	Proceedings of 2nd Int. Conf. on Permafrost, North American Contribution, Yakutsk, U.S.S.R. National Academy of Sciences, Washington, D.C., pp 310-317.	1973	198

LIST OF TECHNICAL PUBLICATIONS

ARCTIC GEOTECHNIQUE

Title	Author	Publication	Publication Date	Page No.
An Investigation of Core Drilling in Perennially Frozen Gravels and Rock	Lange, G.R.	U.S. Army, CRREL, Tech. Rpt. 245, Hanover, N.H., 31p.	1973	199
Origin, Composition, and Structure of Perennially Frozen Ground and Ground Ice: A Review	MacKay, J.R./Black, R.F.	Proceedings of 2nd Int. Conf. on Permafrost, North American Contribution, Yakutsk, U.S.S.R., National Academy of Science, Washington, D.C., pp 71-100.	1973	200
Design of an LNG Terminal in Canada's High Arctic	McDonald, A.F.	In Ports '80, Proc. ASCE, pp 488-503.	1980	201
Frost Cell Design and Operation	Mageau, D.W./Sherman, M.B.	Proceedings 4th Int. Conf. on Permafrost, Fairbanks, AK, National Academy Press, Washington, D.C., pp 767-772.	1983	202
Geophysical Measurement of Subbottom Permafrost in the Canadian Beaufort Sea	Morak, J.L./MacAuley, H.A./Hunter, J.A.	Proceedings 4th Int. Conf. on Permafrost, Fairbanks, AK, National Academy Press, Washington D.C., pp 866-871.	1983	203
Thaw-Consolidation Tests on Remoulded Clays	Morgenstern, N.R./Smith, L.B.	Canadian Geotechnical Journal, Vol. 10, No. 1, pp 25-40.	1973	204
Soil Stabilization for Protection of Sea-bed Structures from Ice Scour	Morgenstern, N.R./Sterne, K.	Report to Boreal Institute for Northern Studies, Edmonton, Alberta 39p.	1980	205
Thaw-Consolidation Tests on Undisturbed Fine-Grained Permafrost	Nixon, J.F./Morgenstern, N.R.	Canadian Geotechnical Journal, Vol. 11, No. 1, pp 202-214	1974	206
Cone Penetration Testing and Experience	Norris, G.M./Holte, R.D., editors	Proceedings of a session sponsored by the Geotechnical Eng. Div. of ASCE, St. Louis, Missouri, ASCE, New York, N.Y., 479 p.	1981	207

LIST OF TECHNICAL PUBLICATIONS

ARCTIC GEOTECHNIQUE

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Subsea Permafrost at Prudhoe Bay, Alaska: Drilling Report and Data Analysis	Osterkamp, T.E./ Harrison, W.D.	University of Alaska, Geophysical Institute Rpt R-245, 69p.	1976	209
Temperature Measurements in Subsea Permafrost off the Coast of Alaska	Osterkamp, T.E./ Harrison, W.D.	In the Roger J.E. Brown Memorial Volume, Proc. 4th Can. Permafrost Conf., Calgary, National Research Council of Canada, Ottawa, pp 238-248.	1981	210
The Measurement of Unfrozen Water Content by Time Domain Reflectometry: Results from Laboratory Tests	Patterson, D.E./Smith M.W.	Canadian Geotechnical Journal, Vol. 18, No. 1, pp 131-144.	1981	211
Guide to a Field Description of Permafrost for Engineering Purposes	Pihlainen, J.A./ Johnston, G.H.	National Research Council of Canada Associate Committee on Soil and Snow Mechanics, Tech. Memo. 79, 23p.	1963	212
Communications of Data from Project Files on Churchill Harbour, Proposed Coppermine Docks, Cambridge Bay Wharf, Inuvik Wharf, Norman Wells Wharf, Yellowknife Wharf and Hay River Wharf	Public Works Canada,	Edmonton, Alberta	1983	213
Determination of the Thermal Properties of Frozen Soils	Riseborough, D.W./ Smith, M.W./Halliwell, D.H.	Proceedings 4th Int. Conf. on Permafrost, Fairbanks, AK, National Academy Press, Washington D.C., pp 1072-1077.	1983	214

LIST OF TECHNICAL PUBLICATIONS

ARCTIC GEOTECHNIQUE

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Techniques for Core Drilling in Frozen Soils	Roggensack, W.D.	Proc. Symposium on Permafrost Field Methods and Permafrost Geophysics, National Research Council, Canada, Associate Committee Geotechnical Research, Tech. Memo. 124, pp 14-24.	1979	215
Prediction of Pile Performance in Permafrost Under Lateral Load	Rowley, R.K./Watson, G. H./Ladanyi, B.	Canadian Geotechnical Journal, Vol. 12, No. 4, pp 510-523.	1975	216
Experiences with Engineering site Investigations in Northern Quebec and Northern Baffin Island	Samson, L./Tordon, F.	Proceedings 3rd Can. Conf. on Permafrost, National Research Council, Associate Committee on Geotechnical Research, Tech. Memo 96, pp 21-38.	1969	217
Geophysics in the Study of Permafrost	Scott, W.J./Sellman P.V./Hunter, J.A.	Review Paper, Proc. 3rd Int. Conf. on Permafrost, Edmonton, Alberta, Vol. 2, National Research Council of Canada, Ottawa pp 93-115.	1978	218
Protection of Permafrost and Ice Rich Shores, Tuktoyaktuk, N.W.T., Canada	Shah, V.K.	Proceedings of 3rd Int. Conf. on Permafrost, Edmonton, Alberta, National Research Council of Canada, Ottawa, pp 870-876.	1978	219
Heat and Salt Transport Processes in Thawing Subsea Permafrost at Prudhoe Bay, Alaska	Swift, D.W./Harrison, W.D./Osterkamp, T.E.	Proceedings 4th Int. Conf. on Permafrost, Fairbanks, AK, National Academy Press, Washington, D.C., pp 1221-1226.	1983	220
Earthquake Engineering	Wiegel, R.L., editor	Prentice-Hall, Inc., Englewood Cliffs, N.J., 518p.	1970	221

SOURCE

Advisory Committee on Northern Development
"Western Arctic Moderate Draft Harbour"
Transportation Committee Steering Group on Marine
Transportation
1977

SUMMARY

ACND Transportation Committee undertook a study of the requirements for and cost of a moderate draft (20 feet) facility in the Western Arctic.

The study examines sixteen possible sites between Herschel Island and Paulatuk on the basis of operational acceptability, hydrography, meteorology, ice regime, infrastructure, environmental impact and costs. In view of an apparent lack of interest and requirements among other prospective users, it was considered that the CANMAR requirements for hydrocarbon exploration were representative in general of moderate draft port requirements and were therefore used as a basis for the study.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Design Considerations of Structures

SOURCE

Andersland, O.B./Anderson, D.M.
Geotechnical Engineering for Cold Regions
McGraw Hill, New York, N.Y., 566p.
1978

SUMMARY

In responding to the need for geotechnical information on seasonally and permanently frozen ground, this is the first book to utilize current research in North America as the basis for a comprehensive survey of theoretical and practical aspects of geotechnical engineering for cold regions. Leading authorities from the United States and Canada have contributed to this text which is designed for readers who are already familiar with the physical and mechanical properties of unfrozen soil. The first two chapters of the book provide an introduction to general features of cold regions and special engineering considerations. The discussion of ground thermal regime includes prediction of the long term temperatures which are required for proper foundation design and the thawing or freezing beneath heated or cooled areas. Consideration of mechanical properties of frozen ground includes treatment of stress-strain-time relationships, strength for a given service life, and the temperature effect on creep rate and strength. Foundation problems include design considerations, bearing capacity, shallow and pile foundations, ground anchors, frost heave forces, and pavement structures for cold regions. Landslides in permafrost are classified; and slopes in thawing permafrost and in frozen soils, as well as factors contributing to slope instability, are discussed.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Permafrost Engineering

SOURCE

Anderson, D.M./Morgenstern, N.R.
"Physics, Chemistry, and Mechanics of Frozen Ground: A Review"
Proceedings 2nd Int. Conf. on Permafrost, North American
Contribution, Yakutsk, U.S.S.R., National Academy of
Sciences, Washington, D.C., pp 257-288
1973

SUMMARY

The present review is concerned primarily with developments since 1963. Attention is focused on work done in North America; developments elsewhere will be reviewed by others in companion papers in this volume.

Care has been taken to avoid overlooking significant advancements and new developments. Because of spatial constraints however, the literature citations are not exhaustive. However, this shortcoming is somewhat mitigated in that a nearly exhaustive bibliography can be constructed from the combined references contained in the publications that have been cited. Priority has been given to contributions appearing in the open literature. Communications of limited availability, such as reports distributed by corporations, academic institutions, and government agencies, are cited when no journal citation is possible and the importance of the development reported warrants it. The section on thermal aspects of frozen ground is not fully developed since this important topic is being treated in Session I of the Conference.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Physical Characteristics

SOURCE

Are, F. E.
"Subsea Cryolithozone of the Arctic Ocean"
U. S. Army CRREL, Draft Translation 686,
Hanover, N.H., 26p.
1978

SUMMARY

The cryolithic zone is the designation for a zone of the Earth's crust having a negative temperature; the frozen rocks are rocks which contain ice; the cold (frost) rocks are rocks whose temperature is below zero but which do not contain ice. ... a cryolithic zone is extensively developed below the bottom of the Arctic Ocean and its fringe seas. However, the geocryological study of the sea bottom is extremely deficient. Reports about the distribution, properties and developmental principles of rocks of the sea bottom cryolithic zone have already long been necessary to support navigation through the northern maritime routes and for the construction of ports. Their requirement has sharply increased in connection with the initiated conquest of natural resources of the Arctic shelf. The enormous practical significance, poorly studied (sic) nature and poor access of the subsea cryolithic zone render its investigation one of the most interesting and pressing problems of modern cold research.

KEY WORDS	CLASSIFICATION
Arctic Geotechnique	Permafrost Distribution

SOURCE

Baker, T.H.W.
"Transportation, Preparation and Storage of Frozen Soil
Samples for Laboratory Testing"
ASTM, Spec. Tech. Publ. 599, pp 88-112
1976

SUMMARY

Increased construction activities in cold regions require a better understanding of the behavior of frozen soil. Although in situ testing procedures are being improved or developed, the highly variable and complicated conditions usually encountered in the field make it difficult to formulate interpretations that are useful in practice. Controlled laboratory tests on frozen soils are helpful, therefore, in determining behavior indicative of diverse field conditions and will assist in establishing design information. This paper is a review of the procedures used and the difficulties encountered in the transportation, preparation, and storage of naturally and artificially frozen soil samples required for testing in the laboratory. The effective control of sample disturbance by temperature variation and sublimation and the need for further investigation as to their effect on the mechanical properties of frozen soil are discussed.

KEY WORDS	CLASSIFICATION
Arctic Geotechnique	Subsurface Exploration Laboratory Testing

SOURCE

Blouin, S.E./Chamberlain, E.J./Sellman, P.V./Garfield D.E.
"Penetration Tests in Subsea Permafrost, Prudhoe Bay, Alaska"
U.S. Army, CRREL, Rpt. 79-7, Hanover, N.H., 45p 1979

SUMMARY

Sediments beneath the Beaufort Sea near Prudhoe Bay, Alaska, were probed at 27 sites using a static cone penetrometer to determine engineering properties and distribution of material types, including ice-bonded sediments. The probe provided both point and casing resistance data and thermal profiles. At five sites these data were correlated with information from adjacent drilled and sampled holes. These control data and the quality of the probe information permitted profiles of sediment type and occurrence of ice-bonded material to be developed along three lines that included various geological features and depositional environments. The penetration data obtained can be used to aid in the design of shallow and deep foundations in both ice-bonded and unfrozen subsea sediments.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Subsurface Exploration In-Situ Testing

SOURCE

Brown, R.J.E.
"Permafrost in Canada: Its Influence on Northern Development,"
University of Toronto, Press, Toronto, 234p
1970

SUMMARY

Permafrost is the thermal condition of the earth's crust when its temperature has been below 32°F continuously for a number of years. Half of Canada's land surface lies in the permafrost region - either in the continuous zone where the ground is frozen to a depth of hundreds of feet, or in the discontinuous zone where permafrost is thinner, and there are areas of unfrozen ground.

The existence of permafrost causes problems for the development of the northern regions of all countries extending into the Arctic. Mining operations are hindered by frozen ore which resists blasting and is difficult to thaw. Agriculture is restricted by the presence of permafrost near the ground surface which limits the soil available for plant growth. Engineering structures are also affected by the low temperatures. Ice layers give soil a rock-like structure with high strength. However heat transmitted by buildings often causes the ice to melt, and the resulting slurry is unable to support the structure. Many settlements in northern Canada have examples of structural damage or failure caused by permafrost. In the construction and maintenance of railways, buildings, water and sewage lines, dams, roads, bridges, and airfields, normal techniques must often be modified at additional cost because of permafrost.

For the the last twenty-five years scientific investigations and engineering projects have increased steadily in Canada's permafrost region, and it is now technically possible to build any structure or conduct any activity on the worst soils and under permafrost conditions.

This comprehensive analysis of permafrost - its orign, definition, and occurrence, and the effect it has on industry and agriculture - will be invaluable to the growing number of people working in the north and to those interested in its development.

KEY WORDS	CLASSIFICATION
Arctic Geotechnique	Permafrost Distribution Permafrost Engineering

SOURCE

Brown, R.J.E./Kupsch, W.O.
"Permafrost Terminology"
National Research Council, Canada, Associate
Committee Geotechnical Research, Tech. Memo 111,
62p.
1974

SUMMARY

A list of terms related to permafrost is compiled in an attempt to meet the need for standardized terminology. A total of 237 selected items are given, of which 146 are defined terms, 38 are cross-referenced to the defined terms and 53 are inverse word order listings. Supplementary comments are given with many definitions, references are provided for some and a few photographs and diagrams are included for additional information and clarification.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Permafrost Terminology

SOURCE

Brown, R.J.R./Pewe. T.L.
"Distribution of Permafrost in North American and its
Relationship to the Environment: A Review 1963-1973"
Proceedings of 2nd Int. Conf. on Permafrost, North
American Contribution, Yakutsk, U.S.S.R., National
Academy of Science, Washington, D.C., pp 71-100
1973

SUMMARY

This review summarizes progress from 1963 to 1973 in knowledge of the distribution of permafrost and the relation of enviornmental factors in North America. The factors examined are climatic relationships and terrain relationships. Ground ice features, other periglacial features, past distribution of permafrost and chronology of permafrost are also discussed. Finally recommendations for future work are given.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Genesis, Permafrost Distribution

SOURCE

Canadian Geotechnical Society
"Canadian Foundation Engineering Manual"
Canadian Geotechnical Society, Montreal, Quebec, Canada
1978

SUMMARY

The Canadian Foundation Enginering Manual provides suggested procedures to be followed in the design installation, and construction of foundations with a view to ensuring safety, quality, economy, and fitness for purpose.

The Manual has been arranged in four parts which presents various aspects of foundation engineering.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Foundation Analyses

SOURCE

Chamberlain, E.J./Sellmann, P.V./Blouin, S.E./Hopkins,
D.M./Lewellen, R.I.
"Engineering Properties of Subsea Permafrost in the
Prudhoe Bay Region of the Beaufort Sea"
Proceedings 3rd Int. Conf. on Permafrost, Edmonton,
Alberta, Canada, National Reserach Council of
Canada, Ottawa, pp 629-635
1978

SUMMARY

Core samples, cone penetration resistance and temperature data obtained from subsea sediments near Prudhoe Bay, Alaska, provided the basis for this study. The sites were located 1 to 17 km from shore in 2 to 12 m of water. Maximum hole depth was 50 m. The materials at the drill sites included sands and gravels overlain by 4.5 to 7.5 m of silts and clays. No ice-bonded materials were observed, although thermal data indicated that permafrost was present. Index property, triaxial compressive strength, consolidation and permeability data were obtained in the laboratory. Strengths ranged between 25 and 270 kPa for the fine material. Highly overconsolidated clays were encountered at the site farther from shore. The preconsolidation pressure was estimated to be 1.5 MPa. Based on considerations of geologic and climatic history, it is proposed that the over-consolidation is a result of freezing and thawing.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Physical Characteristics Subsurface Exploration

SOURCE

Chamberlain, E.J.
"Site Investigations and Submarine Soil Mechanics
in Polar Regions"
U.S. Army, CRREL, Spec. Rpt. 81-24, Hanover, N.H.,
18p. 1981

SUMMARY

Placing oil exploration and production structures offshore in the Alaskan Beaufort Sea will require careful site investigation and evaluation of submarine soil mechanics. Ice-bonded permafrost occurs widely under the Beaufort Sea floor. Its engineering properties are important to the design of offshore structures. Highly overconsolidated clays also occur widely and interfere with access to gravels for constructing artificial islands. Sites should be selected to avoid ice-rich permafrost. Laboratory tests may need to be conducted to determine the potential hazards of thaw consolidation and weakening.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	General Scope

SOURCE

Clark, J.I., Shields, D.H., Graham, J., Rymes, J.E.
"Cold Regions Engineered Earthworks"
Transportation Development Centre, Contract No. 4927, File No. 01465-410
1983.

SUMMARY

The report is a study of cold region engineered earthworks in Canada and presents:

a) the current state-of-the-art of engineering earthworks in cold regions.

b) describes and evaluates on-going research in this field.

c) a detailed outline, including cost estimates of a research and development strategy which would enable Canada to master the art of cold climate earthworks.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Design Considerations

SOURCE

Cornfield, G.M.
"Sheet Pile Structures"
in Foundation Engineering Handbook, H.F. Winterkorn
and H.Y. Fang, editors, Van Nostrand Reinhold Co.,
Toronto, Ontario, Canada, pp 418-444.
1975

SUMMARY

This part of the Foundation Engineering Handbook provides an overview of the various pile sections available. Their efficiency and their uses are discussed. The design principles of anchored sheet pile walls are discussed with respect to soil and water pressures and modes of failure. Conventional design methods are reviewed for anchored and cantilever structures with a special section on anchorage design. Practical considerations regarding the life of structures and construction are discussed.

KEYWORD	CLASSIFICATION
Arctic Geotechnique	Foundation Analysis

SOURCE

Davison, B.E./Rooney, J.W.
"Use of Thermal Piles for Offshore Frozen Embankments"
Proc. 4th Int. Conf. on Port and Ocean Engineering
Under Arctic Conditions, Vol. 1, Ocean Engineering
Info Centre, Memorial University, St. John's,
Nfld., pp 358-369.
1978

SUMMARY

This paper briefly discusses concepts for the design and construction of an offshore gravel embankment utilizing thermal piles in water depths of less than 60 feet. Particular emphasis is placed on the effect of short and long term thermal considerations which could be expected to influence the performance of a man-made island in offshore areas underlain by permafrost as well as in areas free of permanently frozen soil.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Design Considerations

SOURCE

Dismuke, T.D.
"Cellular Structures and Braced Excavations"
in Foundation Engineering Handbook, H.F. Winterkorn and
H.Y. Fang, editors, Van Nostrand Reinhold Co., Toronto,
Ontario, Canada, pp 445-480
1975

SUMMARY

This Chapter of the Foundation Engineering Handbook provides an overview of the design and construction aspects of cellular structures and braced excavations. Cellular structures, as covered in this Chapter, are earth-filled circular, semi circular, or diaphragm cells constructed of flat or shallow arch web steel sheet piling. Braced excavations are retained excavations with vertical sides.

Both types of structures have certain common features. The piling is usually driven to given tip elevation, and structure movements are large. In addition, methods for the determination of earth pressures and pressure distribution are primarily empirical and state of the art for predicting performance is sometimes poor.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Foundation Analyses

SOURCE

Department of Public Works
"Hershel Island, Feasibility of a Marine Terminal"
Report, Ottawa, 141p
1970

SUMMARY

The field surveys, investigations and studies summarized in this report were directed toward a study of the engineering feasibility of designing and building a deep-water marine oil terminal for year-round operations in the Arctic.

The study was concentrated principally on a location in the area of Herschel Island, Yukon Territory. However, since little reliable information was available on site conditions in this area, alternative locations were selected early in the study to provide for the possibility of unfavourable findings at Herschel Island.

For the most part, requirements were considered for ice breaking tankers of the 326,000 DWT class, operating at fully loaded draughts of 76 ft. Included was a permanent type wharf at which these tankers could berth, equipment on the wharf to load them quickly and efficiently and submarine pipelines connecting petroleum storage facilities on land and the marine loading terminal. Onshore petroleum storage (tank farms) was not studied but the availability of contiguous land suitable for this purpose was included in the site selection criteria.

Economic feasibility was not studied due to the many unknown factors outside the scope of this report which would influence annual costs and revenues.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Design Considerations

SOURCE

Domaschuk, L./Marr, C.S./Shields, D.H./Yong, G.
"Creep Behavior of Frozen Saline Silt Under Isotropic
  Compression"
Proceedings 4th Int. Conf. on Permafrost, Fairbanks,
  AK, National Academy Press pp. 238-243 1966

SUMMARY

Isotropic compression creep tests were conducted on a prepared frozen sandy silt with a pore-fluid salinity of about 60 parts per thousand before freezing. Single-step and multi-step loadings of pressure from 70 to 700 kPa were applied to soil samples at three different temperatures (T = -15°C, -10°C, -5°C). From our results we observed the following: (1) Samples originally in equilibrium underwent attenuating creep upon compression by a superimposed hydrostatic stress; over 70% of the ultimate volume change occurred within the first few hours; a substantial portion of the volume change was not recovered upon unloading. The level of ultimate volume change indicated that volume change during creep could be a significant factor in some problems. (2) A history of loading and recovery had a strain-hardening effect on the frozen soil; so did a history of incremental loading. (3) At -5°C the saline soil was non-bonded but its response to isotropic compression did not seem to be qualitatively different from the way it behaved when it was ice-bonded. This study is part of a broader investigation into the long-term multiaxial creep behavior of frozen saline soils that simulate those beneath the Beaufort Sea.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Physical Characteristics Laboratory Testing

SOURCE

Douglas, R.J.W.
"Geology and Economic Minerals of Canada"
Economic Geology Report No. 1, Queens's Printer for
  Canada, Geological Survey of Canada, Ottawa, 838p.
1970

SUMMARY

This fifth edition of Geology and Economic Minerals of Canada presents a general review of our present knowledge of the geology of Canada. It has been possible for the first time to treat many different aspects of the geology in considerable detail on a nation-wide basis, and to attempt a tectonic synthesis of the four major geological regions - the Canadian Shield, and the bordering Phanerozoic platforms and orogens of southeastern, western, and arctic Canada. The accompanying folio contains a geotectonic correlation chart for each of those regions and eight maps at 1:5 million scale dealing with the geology, tectonics, mineral deposits, glacial features, physiography, isotopic ages, and magnetic and gravity anomalies. In the text, factual data are concisely summarized and economic and scientific interpretation and conclusions are clearly separated.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Physiographic Regions

SOURCE

Fang, H.Y./Dismuke, T.D, ed.
"Design and Installation of Pile Foundations and Cellular
Structures"
Proceedings of Conference on Design and Installation of
Pile Foundations and Cellular Structures, ENVO Publishing
Co., Inc., Lehigh Valley, Penn., U.S.A., 447p.
1970

SUMMARY

Numerous papers have been written and several conferences held on the subject of pile foundations. However, the information has not been inclusive enough to cover many facets which affect the design and installation of a satisfactory pile foundation.

In contrast to the information available on pile foundations there is little published information on the subject of cellular structures and this has largely been restricted to design considerations. The growing importance of cellular structures makes it imperative that additional information become available.

It was the intent that for pile foundations the review should start with the foundation requirements imposed by the supported structure, sequentially progress through the other pertinent considerations and conclude with the pile installation. For cellular structures it was desired that the review should begin with basic design methods and end with installation practice.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Foundation Analyses

SOURCE

Hailey, D.W.
"Site Evaluation for Artificial Drilling Island in
the Beaufort Sea"
1st Canadian Conference on Marine Geotechnical
Engineering, Calgary, Alberta, Canada
1978

SUMMARY

This paper describes the evolution in site investigation practice for artificial drilling islands in the southern Beaufort Sea. The four types of island construction methods that have been used are reviewed. Site evaluation requirements are described with specific reference to criteria for acceptance of submarine sand for island fill.

Prior to 1978, planning and construction of drilling islands lay within the region of landfast ice. Site investigations for these islands were invariably carried out during the winter months from the ice surface. The paper describes two drilling and sampling methods that have been used to delineate seabed soil conditions with ice-based data collection programs.

The field methods adopted to evaluate the Issungnak site, which lies in 20 metres of water, are described. This island site is located on the fringe of the landfast ice, where conditions were found to be unsafe for an ice-based drilling program. A unique marine drill was fabricated for this project. A variable frequency oscillator was used to drive a sampling tube into the seabed. The paper describes the evolution of this drill, and its operation with brief reference to the field performance.

KEY WORD	**CLASSIFICATION**
Arctic Geotechnique	Design Considerations Subsurface Exploration

SOURCE

Heidebrecht, A.C./Basham, P.W./Rainer, J.H./
Berry, M.J.
"Engineering Applications of New Probabilistic Seismic
Canadian Journal of Civil Engineering, Volume 10, pp. 670-680
1983

SUMMARY

New Peak Horizontal acceleration and velocity zoning maps with a probability of exceedance of 10% in 50 years and seven seismic zones are developed from new probabilistic strong seismic ground-motion estimates for replacement of the 1970 seismic zoning map in the National Building Code of Canada. The adoption of a probability of exceedance of 10% in 50 years produces reference seismic ground motion appropriate to the level of protection afforded by provisions of the current code; the use of two ground-motion parameters, the relative levels of which vary considerably throughout the country, provides independent reference levels for structures having short and long fundamental periods.

For calculating seismic base shear, a new seismic response factor is derived in which seismic forces for long-period structures are directly proportional to zonal velocities, and for short-period structures proportional to zonal accelerations, with an upper limit on the acceleration/velocity ratio applicable for any location. To maintain the same design standard as provided by the current code, the base shear is calibrated to remain the same, on average, in large population centres in regions of moderate to high seismic risk. The resulting changes in the base shear applicable at various locations reflect the improved estimates of seismic risk, in particular the introduction of additional zones in the higher risk regions of the country and the higher levels of short period ground motion estimated for some regions of eastern Canada.

These and associated changes in seismic design provisions have been recommended for adoption in the 1985 edition of the National Building Code of Canada.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Seismicity

SOURCE

Holubec, I./McDonald, A.F.
"Geotechnical Aspects in an Arctic Wharf Design"
33rd Can. Geot. Conf., Calgary, Alberta, Canada
1980

SUMMARY

Proposed transportation of natural gas from the high arctic by ice breaking capable ships requires construction of LNG Terminals with wharfs in the Arctic Islands. The primary criteria for locating these Terminals is naturally first the presence of gas followed by sufficient water depth, protection from ice floes and sheets, and finally sea bottom conditions. Generally, the sea bottom conditions in the high arctic in the present gas find areas are poor consisting of soft clays and very loose sands. Since it is difficult to find a terminal site which meets all the criteria, it is frequently necessary to design the terminal for less than ideal soil conditions.

This paper discusses the sea bottom conditions at Petro Canada's proposed LNG Terminal and the process of developing an acceptable Terminal consisting of a wharf and barge containment areas. The structures, aside from standard stability and settlement considerations, have to be constructible in the arctic conditions, withstand large ice and seismic forces and be stable under both thawing and freezing thermal changes.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Permafrost Distribution Design Considerations

SOURCE

Huck, R.W./Hull, J.R.
"Resonant Driving in Permafrost",
Foundation Facts, vol. 7, no. 1, pp 11-15
1971

SUMMARY

The results of these preliminary tests prove the feasibility of installing piles in permafrost using the high frequency BRD-100 vibratory driver. Moreover, the BRD-100 causes minimal upset to the thermal regime and is an excellent tool for recovering core samples of permafrost to considerable depths. For a production operation, modifications to the BRD set-up would provide greater flexibility and eliminate the restrictions imposed by the limitations of the preliminary test equipment.

The Bodine Resonant Driver is available in a larger size with a ratio of up to one thousand horsepower (BRD 1000). Some prior tests which involved installing 50-foot open-end pipe and H piles in 25°F artificially frozen soils using the BRD-1000 produced very satisfactory results.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Pile Installation

SOURCE

Hunter, J.A.,/Judge, A.S./MacAuley, H.A./Good, R.L./
  Gagne, R.M./Burns, R.A.
"The Occurence of Permafrost and Frozen Sub-seabottom
  Materials in the Southern Beaufort Sea"
Environment Canada, Beaufort Sea Project, Tech. Rpt.
  22, Victoria, B.C. 174p.
1976

SUMMARY

Permafrost conditions exist beneath most of the Beaufort Sea shelf area. As a result of large changes in the surface thermal regime in the recent geological past, non-equilibrium conditions are probably found in most areas; hence permafrost is both aggrading and degrading. Permafrost is generally at much higher temperatures offshore than the equivalent permafrost conditions onshore and as a result is much more susceptible to thawing by a thermal disturbance. The occurrence of ice-rich sub-seabottom sediments over large areas of the shelf has been interpreted from seismic data. Such sediments are potentially susceptible to hazardous thermal degradation. Because of low sediment temperatures, natural gas in shallow sediments may be found in the form of clathrate hydrates, which may cause additional technical problems for exploratory drilling.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Permafrost Distribution

SOURCE

Iskandar, I.K./Osterkamp, T.E./
Harrison, W.D.
"Chemistry of Interstitial Water from the Subsea
Permafrost, Prudhoe Bay, Alaska"
Proceedings of 3rd Int. Conf. on Permafrost,
Edmonton, Alberta, Canada, National Research
Council of Canada, Ottawa, pp 92-98
1978

SUMMARY

Interstitial water from Prudhoe Bay subsea sediments extracted by gravity settling and centrifugation was analyzed with depth for salinity (specific conductance) and selected chemical parameters. Six holes under the seabed, one hole on the beach and one hole on land were sampled during two drilling projects...In general, all conductivity values of interstitial water from subsea permafrost were considerably higher than those of solutions from land-based permafrost. Selected sediment characteristics of potential importance in studying the chemistry of interstitial water such as field measurement of temperature, organic carbon content, calcium carbonate content and particle size analysis are discussed.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Chemical Characteristics

SOURCE

Johnston, G.H.
"Permafrost Engineering Design and Construction"
Associate Committee on Geotechnical Research,
National Research Council of Canada, John Wiley
and Sons, Toronto, 540p.
1981

SUMMARY

Many studies and investigations have been carried out on permafrost and the northern terrain by government and industry. Based on the information and experience gained from these studies, the National Research Council of Canada has prepared this book to provide guidance to those involved in permafrost engineering. Principles and methods that can be applied in the design and construction of various types of foundations and facilities are described. The first four chapters deal with the main factors that affect engineering operations in the North, such as the climate, terrain features, permafrost features and the properties and behaviour of frozen ground. The next six chapters deal with the more practical aspects of permafrost engineering, such as project planning, site investigations, frozen ground excavation and placement and the design and construction of various engineering works.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Permafrost Engineering

SOURCE

Ladanyi, B.
"Use of the Static Penetration Test in Frozen Soils"
Canadian Geotechnical Journal, Volume 13, No. 2,
pp 95-110
1976

SUMMARY

Within the scope of a study on the use in frozen soils of some geotechnical field investigation methods, a series of deep, static and quasi-static, penetration tests was carried out in July 1974 at a permafrost site near Thompson, Manitoba. The field study included stress - and penetration rate - controlled tests, performed with an electric penetrometer, as well as several short-term and stage-loaded pressuremeter tests. The study shows that a static penetration test can furnish valuable information on the time-dependent strength of frozen soil, provided the test is conducted either with a very accurate control of the penetration rate, or as a stage-loaded test. It is considered that a comparison of frozen soil strengths deducted from such a test, with those determined by pressuremeter tests or triaxial compression tests, can only be made at comparable strain rates. An attempt was, therefore, made in the paper to find a relationship between the penetration rate and an equivalent time to failure for the soil surrounding the penetrometer tip, which enabled this comparison to be carried out.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Subsurface Exploration

SOURCE

Ladanyi, B./Johnston, G.H.
"Evaluation of In-situ Creep Properties of Frozen Soils
with the Pressuremeter"
Proceedings of 2nd Int. Conf. on Permafrost, North American Contribution,
Yakutsk, U.S.S.R., National Academy of Science, pp. 310-317.
1973

SUMMARY

For the design of foundations and other engineering structures in permafrost areas, there has been a real need for new methods and instruments to determine the properties of frozen soils in the field. A research project was undertaken, therefore, in 1971 to investigate the suitability of the Menard pressuremeter, as a tool for in-situ evaluation of the rheological properties of frozen soils. Although the pressuremeter has been used extensively in unfrozen soils and rock, the authors were not aware of any published information that describes its use for investigating the basic creep behaviour of frozen materials.

It appeared that two kinds of problems had to be solved. First, an appropriate testing procedure had to be developed that would permit the necessary creep information to be obtained with minimum physical and thermal disturbance of the ground. Second, a theoretical interpretation method had to be found that would allow the creep information obtained in a test to be put into a useful general form.

The results of the research investigation carried out are presented in this paper.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Subsurface Exploration

SOURCE

Lange, G.R.
"An Investigation of Core Drilling In Perennially Frozen
Gravels and Rock"
U.S. Army, CRREL, Tech. Rpt. 245, Hanover, N.H., 31p.
1973

SUMMARY

The problems of obtaining frozen samples by core drilling of perennially frozen gravel and rock were investigated. Most of the core drilling was carried out in ice-bonded, well-graded alluvial gravel with the ground temperature near its freezing point using compressed air and oil-based liquids as drilling fluids. The details of both successful and unsuccessful coring attempts are reported and related to descriptions and photographs of samples of a wide range of quality. Drilling variables such as weight on the bit, rotational velocity, rate of penetration, fluid temperatures, viscosities, flow rates and pressures and mechanical details of the diamond bits are reported. To make the information more widely applicable, calculated values for the pressure on the bit, the lineal velocity range of the diamond points, the force per diamond point and the uphole velocity of the fluid stream are given. It is concluded that with careful control of the drilling variables, good samples of these difficult materials can be obtained at satisfactory drilling rates so long as the material is well-bonded by ice. Suggestions are given for improvement of equipment and methods.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Subsurface Exploration

SOURCE

Mackay, J.R./Black, R.F.
"Origin, Composition, and Structure of Perennially
Frozen Ground and Ground Ice: A Review"
Proceedings of 2nd Int. Conf. on Permafrost, North
American Contribution, Yakutsk, U.S.S.R., National
Academy of Science, Washington, D.C., pp 185-192
1973

SUMMARY

The origin of perennially frozen ground (permafrost) and ground ice on land in North America and beneath the sea floor of the Arctic Ocean reflects the geomorphic processes and the thermal variations of the late Quaternary period. Many review papers and books have been published on perennially frozen ground and ground ice since the First International Conference on Permafrost in 1963. This review emphasizes massive ground ice in a brief summary of our state of knowledge of the origin, composition, and structure of permafrost. Deficiencies of knowledge are pointed out, and some recommendations for future study are made.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Genesis Permafrost Distribution

SOURCE

McDonald, A.F.
"Design of an LNG Terminal in Canada's High Arctic"
In Ports '80, Proc. ASCE pp 488-503.
1980

SUMMARY

The Arctic Pilot Project involves natural gas from the Sabine Peninsula on northern Melville Island, which will be pipelined to a liquefaction plant and port facility on the south coast of the island where it will be liquefied. From there, the liquefied natural gas (LNG) will be transported to Southern Canada in ice-breaking LNG ships capable of operating on a year round basis. The LNG plant and associated storage facilities will be constructed on barges and towed to the site. The terminal area is composed of deltaic sands and silts. The soil is in a permafrost condition up to a depth of six feet below mean sea level. This paper deals with the various foundation and logistics problems faced in the evaluation of all alternatives prior to final design.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Design Considerations

SOURCE

Mageau, D.W./Sherman, M.B.
"Frost Cell Design and Operation"
Proceedings 4th Int. Conf. on Permafrost, Fairbanks,
AK., National Academy Press, Washington, D.C. pp.
767-772
1983

SUMMARY

This paper presents the design and recommended operation of a frost heave cell for use in conducting laboratory frost heave experiments. Specific features of the design include split barrel construction for easy assembly, controlled top and bottom temperatures, well-insulated sides, simple thermistor installation for temperature measurement, and new heat exchanger details for top and bottom plates. Tests can be performed on undistrubed samples, remolded cohesive soil, or remolded cohesionless soil. Details of sample preparation are presented for each sample type. Test duration depends on soil type and amount of heave, and generally ranges from 1 to 3 days. Tests can be conducted at various overburden pressures. Test results are interpreted using the Konrad-Morgenstern segregation potential concept of frost heave.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Laboratory Testing

SOURCE

Morack, J.L./MacAuley, H.A./Hunter, J.A.
"Geophysical Measurement of Subbottom Permafrost in the
  Canadian Beaufort Sea"
Proceedings 4th Int. Conf. on Permafrost, Fairbanks,
  AK., National Academy Press, Washington, D.C., pp.
  866-871
1983

SUMMARY

Early marine seismic refraction interpretations on the Canadian Beaufort Sea shelf have indicated the widespread occurrence of ice-bearing sub-seabottom sediments. A large area of the shelf is under lain by coarse-grained high velocity (greater than 3000 m/s, typical of ice-bonded sand and gravel) Cenozoic sediments. Recent data have reaffirmed the subdivision of this area into two major seismic layers, a deep thick continuous layer with the upper surface generally greater than 100 m below the seabottom, and a thin discontinuous layer at depths of 5 - 50 m below the seabottom. High resolution multichannel refraction seismic surveying has provided detailed structure on these layers.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Subsurface Exploration

SOURCE

Morgenstern, N.R./Smith, L.B.
"Thaw-Consolidation Tests on Remoulded Clays"
Canadian Geotechnical Journal, vol. 10, no. 1,
pp 25-40
1973

SUMMARY

A general solution to the problem of one-dimensional thaw-consolidation has been formulated by Morgenstern and Nixon (Can. Geotech. J.8, p. 558, 1971). In order to assess the validity of the theory it was necessary to develop a special oedometer (permode) which could impose the necessary thermal and stress boundary conditions for one-dimensional thaw-consolidation.

The permode permits the measurement of settlements, temperatures at various depths on the side of the sample, and excess pore pressures at the base of the sample during thaw-consolidation.

Controlled thaw-consolidation tests were carried out on three types of remoulded clays. The resulting data showed that the excess pore pressures and the degree of consolidation in a thawing soil depend primarily on the thaw-consolidation ratio. The results obtained demonstrate that the theory adequately represents the soil behavior. Applications of the theory in practice are indicated.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Laboratory Testing

SOURCE

Morgenstern, N.R./Sterne, K.
"Soil Stabilization for Protection of Sea-bed Structures
From Ice Scour"
Report to Boreal Institute for Northern Studies,
Edmonton, Alberta, 39p.
1980

SUMMARY

A laboratory investigation was conducted to determine whether the sea bed in the vicinity of pipelines and drilling platforms could be stabilized by in-situ mixing of the sea bed sediments with cement to a degree sufficient to offer substantial resistance to ice forces.

This process of in-situ mixing of sea bed sediments with cement has been successfully carried out by Takenaka Komuten in Japan who developed the Takenaka Deep Chemical Mixing (DCM) method under the guidance of the Transportation Ministry of Japan.

The results of unconfined compression tests on core samples of cohesive material taken from field tests show an increase in strength by as much as 50 times. However, the success of this method requires the utilization of a wide range of advanced technologies which includes the mixing of the solidifying chemical into a slurry in the plant, feeding the processed slurry to the Deep Chemical Mixer at the site, and mixing it thoroughly and evenly in-situ over the area to be stabilized.

The preliminary laboratory work that was carried out is described in this report. In addition, problems of ice scouring and the formation of pressure ridges were reviewed from the available literature. Finally, the results of the laboratory work are discussed and proposals for further research outlined.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Design Considerations

SOURCE

Nixon, J.F./Morgenstern, N.R.
"Thaw-Consolidation Tests on Undisturbed
Fine-Grained Permafrost"
Canadian Geotechnical Journal, vol. 11, no. 1, pp. 202-214
1974

SUMMARY

A series of thaw-consolidation tests on undisturbed frozen samples of arctic soils is described. The tests were carried out in a special oedometer, and thawing was induced by the application of a sudden constant increase in surface temperature. Settlements, pore water pressures, and rates of thaw are measured, and interpreted in the light of current theories of heat transfer and thaw-consolidation. Excellent agreement is obtained between predicted and observed thaw rates, using published thermal properties. The observed pore pressures and settlements also are consistent with predicted behavior.

These test results on a variety of undisturbed permafrost samples increase the level of confidence when applying the theory of consolidation for thawing soils to natural permafrost deposits.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Laboratory Testing

SOURCE

Norris, G.M./Holtz, R.D., editors
"Cone Penetration Testing and Experience"
Proceedings of a session sponsored by the
Geotechnical Eng. Div. of ASCE, St. Louis,
Missouri, ASCE, New York, N.Y., p 479
1981

SUMMARY

The purpose of the session is to focus the attention of the North American geotechnical engineering profession on various aspects of the cone penetration test: test techniques, applications, evaluation of data, case studies, and recent developments in equipment and procedures.

The volume contains the state-of-the-art report, papers prepared by panel members that deal with a variety of world wide experiences, and a selected set of papers (from a general call for papers) that reflect a variety of largely U.S. and Canadian interests, experiences, and advances in cone penetration testing.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Subsurface Exploration

SOURCE

Nottingham, D./Christopherson, A.B.
"Driven Piles in Permafrost: State of the Art"
Proceedings of 4th Int. Conf. on Permafrost, Fairbanks,
AK, National Academy Press., Washington, D.C.,
pp 928-933.
1983

SUMMARY

Pile driving techniques in permafrost have developed rapidly over the last 5 years, to a point where the driven pile method using thermally modified drilled pilot hole now offers a fast and economical solution to many frozen foundation problems. Most types of piles, including H-shape, pipe, and sheet piles, now can be driven, assuming that there is a knowledge of soil conditions and that the correct procedure is followed. Presented in this paper are the latest research, testing, and production pile driving developments in Alaska. Current proposed pile design approaches will be discussed as related to short-term loading and long-term creep. The scope of this paper is based largely on actual practical experience with about 5,000 piles recently driven in cold and warm permafrost soils; as well as recent laboratory work and field testing experience on a large number of driven piles. The proposed criteria presented in this paper are primarily addressed to the practicing design engineer, including design and construction considerations. As more research and experience accumulate, factors presented in this paper may change.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Design Considerations Pile Installation

SOURCE

Osterkamp, T.E./Harrison, W.D.
"Subsea Permafrost at Prudhoe Bay, Alaska: Drilling Report and Data Analysis"
University of Alaska, Geophysical Institute, Rpt. R-245, 69p.
1976

SUMMARY

A subsea permafrost drilling program conducted near Prudhoe Bay, Alaska, is described. The drilling and sampling procedures, the techniques, analysis and results of the soil studies, temperature measurements, salt concentration measurements, permeability measurements, penetration tests and implication of the results for offshore resource development are also given.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Physical Characteristics Subsurface Exploration

SOURCE

Osterkamp, T.E./Harrison, W.D.
"Temperature Measurements in Subsea Permafrost
off the Coast of Alaska"
In the Roger J.E. Brown Memorial Volume, Proc. 4th
Cdn. Permafrost Conf., Calgary, Alberta, National
Research Council of Canada, Ottawa, pp 238-248
1981

SUMMARY

Temperature measurements have been made in shallow, small-diameter boreholes in the Beaufort, Chukchi, and Bering Seas off the Alaskan coasts since 1975. Methods for making access holes with light-weight equipment are described. These included augering, water jet drilling, rotary water jet drilling and driving. Pipe or tubing was placed in the access holes and logged at discrete, closely-spaced depth intervals, usually one metre, to obtain the temperature profiles.

Temperature profiles in the Norton Sound area of the Bering Sea show that permafrost is absent except possibly very near shore in areas of rapid shore-line retreat. Subzero temperatures were found in all holes drilled in Kotzebue Sound, and in the Chukchi and Beaufort Seas. Holes drilled in the Chukchi Sea near Barrow suggest that the shore-line is stable, or nearly so, and that ice-bearing permafrost is probably thin or absent a kilometer or more off-shore. In the Beaufort Sea (Elson Lagoon) near Barrow, the shoreline is retreating rapidly (i.e. a few metres per year) whereas temperature profiles near Prudhoe Bay suggest a retreat rate of a metre per year or less. The depth to ice-bonded permafrost, as determined by temperature measurements, increases with distance off-shore when the soil conditions are constant. However, ice-bonded permafrost may be found near the sea bed in areas of very fine-grained compact soils even when these occur far offshore. The thermal data has been used to investigate the nature of heat and salt transport processes in subsea permafrost and to construct thermal models which infer its distribution and thickness in a general way.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Permafrost Distribution Temperature Measurements

SOURCE

Patterson, D.E./Smith, N.W.
"The Measurement of Unfrozen Water Content By Time
Domain Reflectometry: Results From Laboratory Tests"
Canadian Geotechnical Journal, Volume 18, No. 1, pp
131-144
1981

SUMMARY

A new technique for determining the volumetric unfrozen water content of frozen soils is reported, which uses time domain reflectometry (TDR) to measure the dielectric property. Using precise temperature control, the technique, which was developed previously by others for unfrozen soils, has successfully applied to the measurement of unfrozen water contents of frozen soils. Curves of the dielectric property versus temperature show a close similarity to unfrozen water content curves, for a variety of soils. Results from experiments on ice-water mixtures and from combined TDR dilatometry experiments on frozen soils suggest that an empirical relationship obtained by Topp, Davis and Annan may be applicable to frozen media as well as unfrozen soils. Using this relationship, dielectric values were converted to unfrozen water content values, and the results agreed very closely with published data for similar soils, determined by other methods. For silt loams, agreement is typically within ± 1 1/2% in volumetric water content, and for clays ± 3%. Some of this difference is undoubtedly due to soil sample variations.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Laboratory Testing

SOURCE

Pihlainen, J. A./Johnston, G.H.
"Guide to a Field Description of Permafrost For
Engineering Purposes"
National Research Council, Canada, Associate Committee
on Soil and Snow Mechanics, Tech. Memo. 79, 23p.
1963

SUMMARY

Almost one half of Canada's total land surface is underlain by permafrost and its existence has many implications to both scientific and engineering interests. Engineering experience has indicated that site investigations are essential in permafrost areas but no standard method for reporting permafrost conditions has been used or is available. This booklet has been prepared with the hope that the descriptive system outlined will fulfill this need. A method for describing the ice phase in perennially frozen materials forms a major part of this "Guide".

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Permafrost Description

SOURCE

Public Works Canada, Western Region
"Communications of Data from Project Files on Churchill
Harbor, Proposed Coppermine Docks, Cambridge Bay Wharf,
Inuvik Wharf, Norman Wells Wharf, Yellowknife Wharf and
Hay River Wharf
Edmonton, Alberta
1983

SUMMARY

Information includes drawings and geotechnical reports and, in a few cases, performance records.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Geotechnical Behaviour of Arctic Structures

SOURCE

Riseborough, D.W./Smith, M.W./Halliwell, D.H.
"Determination of the Thermal Properties of Frozen
Soil"
Proceedings 4th Int. Conf. on Permafrost, Fairbanks,
AK., National Academy Press, Washington, D.C., pp
1072-1077
1983

SUMMARY

This paper describes the development of a method for determining soil thermal properties (conductivity and diffusivity) at temperatures close to 0°C, based upon the transient heat flow from a cylindrical copper probe. A very small heat input and a very sensitive temperature measurement system allow the maximum temperature change in the soil sample to be kept to less than 0.1°C. The soil sample is first cooled to about -10°C, to ensure ice nucleation, and then determinations are done at closely spaced intervals on a warming curve. At each temperature, a least squares regression on the time-temperature data is used to determine the soil properties. The analytical solution is sensitive to both the soil conductivity and the apparent heat capacity; therefore the latter is also determined independently using the unfrozen water content curve obtained via time domain reflectometry. Results for two saturated silts are presented.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Laboratory Testing

SOURCE

Roggensack, W.D.
"Techniques for Core Drilling in Frozen Soils"
Proc. Symposium on Permafrost Field Methods and Permafrost Geophysics, National Research Council, Canada
Associate Committee Geotechnical Research, Tech. Memo. 124, pp 14-24
1979

SUMMARY

The Polar Gas Project has recently undertaken investigations of route conditions for a pipeline to carry natural gas from Melville Island to markets in southern Canada and the United States. The article provides a brief description of two drilling systems that have been designed and developed to meet sampling requirements specific to the Polar Gas route.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Subsurface Exploration

SOURCE

Rowley, R.K./Watson, G.H./Ladanyi, B.
"Prediction of Pile Performance in Permafrost Under
Lateral Load"
Canadian Geotechnical Journal, Volume 12, No. 4, pp
510-523
1975

SUMMARY

In 1971 lateral pile tests were performed at Inuvik, N.W.T. to determine design values in creep for timber and steel pipe piles. Formulation of a theoretical method for prediction of pile load capacity from basic permafrost creep parameters was part of this program.

In 1972 pressuremeter creep tests were performed at the same site so that test pile performance could be predicted independently and compared with measured results. The pressuremeter tests made and the creep parameter values obtained, the predicted pile performance curves and the comparisons with actual test data are presented in this paper.

A Menard pressuremeter was used to determine permafrost creep parameters at an average ground temperature of 29.2°F (-1.6°C). Values for the representative creep modulus and exponents for this soil were derived from the test data. These were used for calculating pressure-deflection curves and subgrade reaction moduli for the laterally loaded piles.

To demonstrate the applicability of the theory, the subgrade reaction moduli derived from the pressuremeter tsts were compared with those deduced directly from the pile load tests. A reasonable agreement was found with the subgrade reaction moduli values obtained for the timber piles. However, the steel pipe piles responded as though the modulus was much higher.

The confirmation field tests were made at a site having ice-rich permafrost whose behavior approaches that of pure ice. To apply the basic theory generally, additional field confirmation tests would be needed, for example, in ice-poor permafrost and covering much longer periods of time.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Subsurface Exploration, Foundation Analyses

SOURCE

Samson, L./Tordon, F.
"Experiences with Engineering Site Investigations
in Northern Quebec and Northern Baffin Island"
Proceedings 3rd Can. Conf. on Permafrost, National
Research Council of Canada, Associate Committee on
Geotechnical Research, Tech. Memo 96, pp. 21-38
1969

SUMMARY

Subsurface investigations were undertaken in permafrost areas in connection with the engineering design of two potential major mining developments in the eastern Canadian Arctic. These are the Asbestos Hill and the Baffin Island Iron Projects.

The subsurface exploration methods are described and subsurface conditions are described at both sites. Ground ice distrituion is discussed for onshore and offshore conditions at both sites.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Permafrost Distribution, Subsurface Exploration

SOURCE

Scott, W.J./Sellman, P.V., Hunter, J.A.
"Geophysics in the Study of Permafrost"
Review Paper, Proc. 3rd Int. Conf. on Permafrost,
Edmonton, Alberta, Vol.2, National Research Council
of Canada, Ottawa, pp 93-115
1978

SUMMARY

In this review of permafrost geophysical techniques emphasis is placed on methods that penetrate into the earth to depths great enough to provide information on permafrost properties or distribution. The emphasis is also on the North American literature and experience. The review covers the period since the Second International Conference held in the Soviet Union in 1973, although in a few cases the period was extended to establish historical perspective. The discussion includes investigations made on land and off shore, based on surface and airborne observations.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Geophysical Exploration

SOURCE

Shah, V.K.
"Protection of Permafrost and Ice Rich Shores, Tuktoyaktuk,
N.W.T. Canada"
Proceedings of 3rd Int. Conf. on Permafrost, Edmonton,
Alberta, National Research Council of Canada, Ottawa,
pp 870-876.
1978

SUMMARY

DPW undertook in May 1972, to study the shore erosion occuring at Tuktoyaktuk and to develop solutions to arrest further degradation of the shore. The program included literature research; review of available data; consultations; field measurements and investigations; and; research on alternative solutions. The investigations revealed that in the Arctic where ice rich soils and massive ice abound within the soil mass, thawing of permafrost and ice caused by the summer temperatures and the summer sea conditions is a principal and additonal cause of shore erosion to those usually encountered in the southern regions. A test solution was devised and implemented in August 1976 to protect the Tuktoyaktuk shore. The first observations show that assumptions made in preparing the solution were reasonable, at least qualitatively. The performance of the test work is to be closely monitored and its adequacy should be adequately known by the time of the conference.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Shore line Erosion

SOURCE

Swift, D.W./Harrison, W.D./Osterkamp, T.E.
"Heat and Salt Transport Processes in Thawing Subsea
Permafrost at Prudhoe Bay, Alaska"
Proceedings 4th Int. Conf. on Permafrost, Fairbanks, AK.,
National Academy Press, Washington, D.C. pp 1221-1226
1983

SUMMARY

The thickness of the subsea thawed layer near the West Dock, Prudhoe Bay, Alaska, and its temperature, pore water salinity and pore water pressure are described. The pressure data are the first of their kind and provide evidence for non-hydrostatic behavior that is probably due to pore water motion. Present knowledge of heat and mass transport mechanisms controlling the thawed layer development is summarized. Heat transport is conductive, but salt transport (necessary because temperatures are negative) is by pore water motion, probably on the order of a few tenths of a meter per year. What drives the motion is still uncertain. Driving by the release of relatively fresh, buoyant water by thawing must occur, but it may not provide enough energy to explain the observations. Driving by surface wave action seems unimportant, at least at the West Dock.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Permafrost Distribution Physical Characteristics

SOURCE

Wiegel, R.L., editor
"Earthquake Engineering"
Prentice-Hall, Inc., Englewood Cliffs, N.J., 518p.
Proceedings 4th Int. Conf. on Permafrost, Fairbanks, A970
1970

SUMMARY

Earthquake Engineering is a collection of articles that summarizes all that is known about earthquakes and resistant design of structures. It is a comprehensive book that provides today's engineer or designer with complete coverage on this geological problem. Many illustrations are included to clarify the material and to dramatize the extent of destruction caused by earthquakes.

The beginning chapters of the book are devoted to man's knowledge of earthquakes, the causes and characteristics of elastic waves, ground motion, and tectonic displacement. These chapters are followed with extensive material on damage, the structural performance of buildings, soil problems and behaviour during an earthquake and tsunamis. There are also descriptions of the dynamic tests that can be made of models and fullscale structures. The final section is devoted to modern design of earthquake-resistant structures, including both soil structures and high-rise structures (steel frame, reinforced concrete, prestressed and precast concrete towers and chimneys) with emphasis on the ductility requirements of these structures. Modern methods of analysis are applied using both linear and nonlinear theory.

KEY WORD	CLASSIFICATION
Arctic Geotechnique	Seismicity

3.0 RESPONSES TO THE ICE ENVIRONMENT

3.1 UTILIZING ICE

LIST OF TECHNICAL PUBLICATIONS

RESPONSES TO THE ICE ENVIRONMENT - UTILIZING ICE

Title	Author	Publication	Publication Date	Page No.
Construction of a Surface-Flooded Ice Wharf	Barthelemy, J. L.	Proceedings - International Symposium on Cold Regions Engineering, 2nd, University of Alaska, 12-14 August 1976. Edited by John Burdick and Philip Johnson, Fairbanks: Cold Regions Engineers Professional Association and Dept. of Civil Engineering, Univ. of Alaska	1977	222
Artificial Sea Ice Structures for Alaskan Ports	Behlike, C. E. McKay, A. R.	ASCE Proc. Civ. Eng. in Oceans, 2nd Conf. Miami Beach, Fla.	1969	223
Mackenzie Delta Ice Road Construction	Betteridge, J. P. Clift, F. W.	Workshop on Winter Roads, 18-19 October, 1979 Ottawa Ontario Edited by N.K. Sinha. Technical Memorandum - Canada, National Research Council. Associate Committee on Geotechnical Research, No. 129	1979	224
Grounded Ice Island: Field and Laboratory Research Final Report/Union Oil Company of California	Duthweiler, F. C. Utt, M. E.	Brea, Calif.: Union Oil Company of California	1976	225
Ice Platform Construction, Resolute Bay, N.W.T., November-December 1974	Fenco Consultants Ltd. Sun Oil Company Ltd.	Calgary: Distributed by APOA, 1975 APOA Project No. 81: Ice Mechanics 1974-75, Arctic Field Test Program, Resolute Bay, North West Territories, Report No. 1	1975	226

LIST OF TECHNICAL PUBLICATIONS

RESPONSES TO THE ICE ENVIRONMENT - UTILIZING ICE

Title	Author	Publication	Publication Date	Page No.
Mechanical Properties of Ice and Their Application to Arctic Ice Platforms	Frederking, R.	Spring Meeting, Eastern Canadian Section, Society of Naval Architects and Marine Engineers, Montreal, April 1975	1975	227
The Construction of Man-Made Drilling Islands and Sheetpile Drillsites in the Alaskan Beaufort Sea	Galloway, D. E. Scher, R. L. Prodanovic, A.	Fourteenth Annual Offshore Technology Conference 1982, proceedings - Dallas: Offshore Technology Conference	1982	228
Load Bearing Capacity of a Floating Drilling Ice Platform: Probabilistic and Reliability Analysis	Hamza, H.	Fourteenth Annual Offshore Technology Conference in Houston, Texas, May 3-6, 1982	1982	229
Ice and Snow Construction: Workpads, Roads, Airfields and Bridges	Keyes, D. E.	Proceedings - International Symposium on Cold Regions Engineering, 2nd, University of Alaska, 12-14 August 1976. Edited by John Burdick and Philip Johnson, Fairbanks: Cold Regions Engineers Professional Association and Dept. of Civil Engineering, Univ. of Alaska	1977	230
Experience in Ice Platform Construction for Arctic Drilling	Masterson, D. M. Baudais, D. J. Wasilewski, B. R.	Fenco Consultants Limited Calgary: Petroleum Society of C.I.M., 1975 Presented at Annual Western Meeting 1975 The Petroleum Society of C.I.M., Edmonton, Alberta	1975	231

LIST OF TECHNICAL PUBLICATIONS

RESPONSES TO THE ICE ENVIRONMENT - UTILIZING ICE

Title	Author	Publication	Publication Date	Page No.
Floating Ice Platform: Offshore Oil Exploration	Masterson, D. M. Kivisild, H. R. Fenco Consultants Ltd.	New York: American Society of Civil Engineers, 1978 ASCE Annual Convention, Chicago, Illinois	1978	232
Creep and Relaxation in Floating Platforms - an Analysis of Case Histories	Masterson, D. M. Strandberg, A. G.	IUTAM Symposium Copenhagen, August 6-10, 1979, Technical University of Denmark	1979	233
Strain Measurements in Floating Ice Platforms and Their Applications to Platform Design	Masterson, D. M. Anderson, K. G. Strandberg, A. G.	National Research Council of Canada	1979	234
Ice Bridges of the James Bay Project	Michel, B. Drouin, M. Lefebvre, L. M. Rosenberg, P. Murray, R.	Ice Mechanics Laboratory, Department of Civil Engineering, Laval University, Quebec, Canadian Geotechnical Journal, Vol. 11, No. 4, 1974	1974	235
Criteria for Constructing Ice Platforms in Relation to Meteorological Variables	Nakawo, M.	Cold Regions Science and Technology, 6 (1983) 231-240	1983	236
The Salinity of Artificial Built-Up Ice made by Successive Floodings of Sea Water	Nakawo, M. Frederking, R.	Ottawa: National Research Council of Canada, Division of Building Research	1982	237
Rational Basis for Design of Floating Ice Roads and Platforms	Peters, D. B. Ruser, J. R. Watt, B. J.	Fourteenth Annual Offshore Technology Conference in Houston, Texas, May 3-6, 1982	1982	238

LIST OF TECHNICAL PUBLICATIONS

RESPONSES TO THE ICE ENVIRONMENT - UTILIZING ICE

Title	Author	Publication	Publication Date	Page No.
Design and Construction of Sea Ice Roads in the Alaskan Beaufort Sea	Potter, R. E. Walden, J. T. Haspel, R. A.	Thirteenth Annual Offshore Technology Conference 1981, proceedings - Dallas: Offshore Technology Conference	1981	239
Design and Analysis of Ice Roads	Shell Oil Company	Report	Unpublished Report	240

SOURCE

Barthelemy, J. L.
"Construction of a Surface-Flooded Ice Wharf"
Proceedings - International Symposium on Cold Regions
Engineering, 2nd, University of Alaska, 12-14 August 1976.
Edited by John Burdick and Philip Johnson, Fairbanks: Cold
Regions Engineers Professional Association and Dept. of
Civil Engineering, Univ. of Alaska, 1977

SUMMARY

In the pioneer days of Antarctic logistics, ships supplying McMurdo Station unloaded cargo on the annual ice at some distance from shore. Thin ice made that operation costly and dangerous. During 1965, favorable ice conditions let icebreakers clear a turning basin along the shore-fast ice of Winter Quarters Bay. The shore-fast ice served effectively as a wharf. For the first time, cargo ships were able to offload onto Ross Island, discharging cargo onto trucks in a conventional, efficient fashion. Subsequently, the shoreline has been used each year for ship unloading, however, due to extensive erosion of the seaward face, it has been necessary to enlarge the natural quay perimeter by attaching various prosthetic extensions. ...At the present time, the Naval Support Force Antarctica is completing an even larger surface-flooded ice wharf in the northeast corner of Winter Quarters Bay. Design criteria and construction procedures for this project have been provided by the Civil Engineering Laboratory. The layout includes overall dimensions of approximately 825 feet along area, a smaller area 500 feet long and 200 feet wide is being reinforced using two layers of one-inch diameter steel cable placed in an overlapping, closed-loop configuration near the neutral axis. Water is delivered to the flood zone by two 1500 GPM electrically driven submersible pumps designed and assembled by the Civil Engineering Laboratory. The target ice thickness is a nominal 20 feet.

KEY WORD	CLASSIFICATION
Utilizing Ice	Ice Platforms - Design Construction

SOURCE

Behlike, C. E.; McKay, A. R.
"Artificial Sea Ice Structures for Alaskan Ports"
ASCE Proc. Civ. Eng. in Oceans, 2nd Conf.
Miami Beach, Fla.
1969

SUMMARY

The purpose of this paper is to focus more popular engineering attention on the problems associated with super-tanker port construction in northern Alaska. It is also the purpose of this paper to focus attention on the possibilities of constructing large port structures from an extremely abundant natural resource-seawater. For brevity this paper will be primarily conceptual and will not deal with some of the more advanced ideas which have been set forth by various engineers.

KEY WORD	CLASSIFICATION
Utilizing Ice	Load Bearing Floating System - Docks & Platforms

SOURCE

Betteridge, J. P.; Clift, F. W.
"Mackenzie Delta Ice Road Construction"
Workshop on Winter Roads, 18-19 October, 1979
Ottawa Ontario
Edited by N.K. Sinha. Technical Memorandum - Canada,
National Research Council. Associate Committee on
Geotechnical Research, No. 129

SUMMARY

Esso Resources Canada Limited's Beaufort exploration drilling program for the winter of 1978-1979 required moving a drilling rig, camp and supplies from Tuktoyaktuk to the middle delta of the Mackenzie River, 40 km west-northwest of Inuvik. ...Other commitments for the drilling rig necessitated tight time frames for lease construction, moving the rig, and drilling the well. As a result, 200 km of river ice road had to be built almost three weeks earlier than had been done in previous years. The presentation will highlight the successful completion of this project. Factors discussed are road site selection, ice testing methods and equipment, road and ice bridge construction and equipment, as well as transportation equipment and techniques used to haul the heavy loads associated with this project.

KEY WORD	CLASSIFICATION
Utilizing Ice	Load Bearing Floating System - Roads

SOURCE

Duthweiler, F. C.; Utt, M. E.
"Grounded Ice Island: Field and Laboratory Research Final Report/
Union Oil Company of California"
Brea, Calif.: Union Oil Company of California, 1976

SUMMARY

This report concerns an ice island built in Harrison Bay, near the Colville Delta off the north coast of Alaska. ...This Final Report covers testing of the island, its performance in spring breakup, and a laboratory experiment on the distribution of salinity during the layered freezing of salt water. ...Our emphasis in this project has been to define the properties of ice frozen from sea water as they relate to the use of ice as a material for engineered structures. The property of principal importance is strength, but because the strength of ice varies with temperature and salinity, considerable effort has gone into measuring those parameters. ...Our experience shows that our concept for a grounded ice island for exploratory drilling in shallow, ice-covered waters is feasible. Our method of island construction produces a drilling site which can be used in exactly the same way as an ice-rich permafrost site on land.

KEY WORD	CLASSIFICATION
Utilizing Ice	Ice Islands and Grounded Systems

SOURCE

Fenco Consultants Limited Sun Oil Company Limited
"Ice Platform Construction, Resolute Bay, N.W.T., November-December 1974"
Calgary: Distributed by APOA, 1975
APOA Project No. 81: Ice Mechanics 1974-75, Arctic Field Test
Program, Resolute Bay, North West Territories, Report No. 1

SUMMARY

In October, 1974, Sun Oil Company retained FENCO to provide engineering services, monitoring and quality control and a final report on construction of five thin ice pads. ...The test program called for ice platforms to be built by freezing thin layers of ice about 100' offshore in the bay area at Resolute. Four of the platforms were 400 ft. by 300 ft. and required 40 inches of ice buildup. The remaining ... was 400 ft. square with 15 inches of built-up ice. ...Besides reading thermistors and thicknesses regularly during flooding, FENCO ... took cores for salinity, density, visual inspection and performed strength tests in the ice. Also weather information was gathered for comparison with growth rates. Data obtained is included in various forms in the appendices...

KEY WORD	CLASSIFICATION
Utilizing Ice	Ice Islands & Grounded Systems - Platforms

SOURCE

Frederking, R.
"Mechanical Properties of Ice and Their Application to Arctic Ice Platforms"
Spring Meeting, Eastern Canadian Section, Society of Naval Architects and
Marine Engineers, Montreal, April 1975

SUMMARY

Natural ice has a number of unusual properties which make it a unique material. Some of these properties, e.g., high homologous temperature, crystallographic structure, and grain structure, are discussed and the manner in which they influence the strength and deformation behavior of ice is considered.

The analytical techniques required to describe the load-bearing performance of a floating ice cover are still being developed. Some of the factors that must be considered in the development of these techniques are illustrated by describing an ice platform that was constructed on sea ice in the high Arctic. The ice platform was used to support an offshore exploratory drilling operation that extended over a period of two months.

KEY WORD	CLASSIFICATION
Utilizing Ice	Ice Islands and Grounded Systems - Platforms

SOURCE

Galloway, D. E.; Scher, R. L.; Prodanovic, A.
"The Construction of Man-Made Drilling Islands and Sheetpile
Drillsites in the Alaskan Beaufort Sea"
Fourteenth Annual Offshore Technology Conference 1982,
proceedings - Dallas: Offshore Technology Conference,
1982

SUMMARY

This paper reviews the design and construction methods, and construction rates for Exxon Company, U.S.A.'s winter 1980-81 construction projects on the North Slope of Alaska. The projects include construction of (1) 90 miles of ice roads (ten-miles on floating ice), (2) two artificial (manmade) gravel islands off the Sagavanirktok River delta in ten-feet and 18 feet water depths, (3) two sheetpile enclosed drillsites on natural barrier islands approximately 60 miles east of Prudhoe Bay, and (4) the development of two upland gravel sources, one near Prudhoe Bay and one near Pt. Thomson. ...Emphasis is given to the unique design criteria and actual construction procedures and production rates for winter constructed manmade gravel islands and the sheetpile enclosed drillsites. These are the two principal alternatives being considered for exploration and development structures in shallow water.

KEY WORD	CLASSIFICATION
Options for Ice Resistant Designs	Floating Structure - Roads Earth Islands

SOURCE

Hamza, H.
"Load Bearing Capacity of a Floating Drilling Ice Platform:
Probabilistic and Reliability Analysis"
Fourteenth Annual Offshore Technology Conference in Houston, Texas,
May 3-6, 1982.

SUMMARY

The long-term response of an artifically thickened drilling ice platform is investigated using a new creep bending finite element model. The ice platform is simulated using thick plate theory, and the fluid support is modelled as a linear Winkler foundation. The numerical results produced by the model have shown good agreement with a small scale load bearing capacity test.

A mathematical technique will be described to perform a probabilistic analysis. This technique allows one to study the effect of a random change in air temperature, grain size, creep properties, elastic properties, and ice cover thickness, on the creep response of ice cover. An empirical formula to predict the central deflection of the ice cover which is based on the field and numerical data is presented which is then combined with the previous technique to carry out a probabilistic analysis of the long term response of the ice cover.

The mathematical details of a formula to predict the time of onset of failure, (time of safe operation) based on the critical strain energy failure criterion, is also presented. The effect of random change of a number of different parameters on the time of safe operation is discussed.

KEY WORD	CLASSIFICATION
Utilizing Ice	Load Bearing Floating Systems - Platforms

SOURCE

Keyes, D. E.
"Ice and Snow Construction: Workpads, Roads, Airfields and Bridges"
Proceedings - International Symposium on Cold Regions
Engineering, 2nd, University of Alaska, 12-14 August 1976.
Edited by John Burdick and Philip Johnson, Fairbanks: Cold
Regions Engineers Professional Association and Dept. of
Civil Engineering, Univ. of Alaska, 1977

SUMMARY

This report is based on observation of the Trans-Alaska Pipeline Project since 1970. Ice and snow can be effectively used as construction materials to build economical, functional, temporary structures to support development projects in arctic and subarctic regions, while reducing commitment of gravel and land resources and conserving energy and other resources. The use of ice and snow for roads, airfields, bridges, and other construction pads has resulted in acceptable environmental disturbances when properly constructed, maintained, and used by environmentally concerned companies. Surface disturbance has caused the majority of environmental losses associated with snow pads. Most disturbances have resulted after late use in the spring or from cutting into banks. Restoration of drainage in the pad before demobilizing in the spring is necessary to prevent unnecessary erosion from occurring.

KEY WORD	CLASSIFCATION
Utilizing Ice	Use of Ice and Snow for Roads, Airfields and Bridges

SOURCE

Masterson, D. M.; Baudais, D. J.; Wasilewski, B. R.
"Experience in Ice Platform Construction for Arctic Drilling"
Fenco Consultants Limited
Calgary: Petroleum Society of C.I.M., 1975
Presented at Annual Western Meeting 1975 The Petroleum Society
of C.I.M., Edmonton, Alberta, October 1975

SUMMARY

...the construction of sea-ice platforms averaging 5 meters (16 feet) thick at the centre has permitted successful offshore drilling in the arctic archipelago at a time when ice conditions prevent the use of conventional offshore rigs. The development of fixed high capacity flooding stations, capable of operating at temperatures of -50 deg. C or lower, and the use of free surface flooding from these stations has contributed to average ice buildup rates of 10 cm/day (4 in/day) during the months of December and January. A review of experience with electric submersible pumps and a discussion of factors affecting the ice growth rate and the apparent superiority of the free-flood method over spraying or sprinkling in the construction of large platforms is presented.

KEY WORD	CLASSIFICATION
Utilizing Ice	Load Bearing Floating Systems - Platforms

SOURCE

Masterson, D.M.; Kivisild, H.R.; Fenco Consultants Limited
"Floating Ice Platform: Offshore Oil Exploration"
New York: American Society of Civil Engineers, 1978
ASCE Annual Convention, Chicago, Illinois, October 16-20, 1978

SUMMARY

Exploratory drilling offshore in the Canadian Arctic Islands in water depths of 60 to 400 m (200 to 1300 ft.) from floating platforms of thickened ice has proven very successful. Designs based on elastic plate theory have been used since the first platform was built in the winter of 1973-74 and correlation between predictions and measurements has been satisfactory. The estimation of long term or creep deflections using reduced modulus concepts has made possible the extrapolation of load test results to other loads and load durations. ...

KEY WORD	CLASSIFICATION
Utilizing Ice	Load Bearing Floating Systems - Platforms

SOURCE

Masterson, D. M.; Strandberg, A. G.
"Creep and Relaxation in Floating Platforms - an Analysis of Case Histories"
IUTAM Symposium Copenhagen, August 6-10, 1979,
Technical University of Denmark

SUMMARY

The use of the natural ice sheet in Arctic regions to support stationary, heavy loads of 500 tons or more for periods of greater than 30 days requires analysis of the flexural creep behaviour of ice. Panarctic Oils Ltd. of Calgary, Canada has, since the spring of 1974, been thickening the natural ice cover by flooding and freezing in thin layers and placing conventional land drilling rigs on these construction platforms. By doing this offshore exploratory drilling for hydrocarbons has proceeded over a great area at relatively little cost. (Baudais, Et. Al. 1974, Baudais, Et. Al. 1976, Masterson and Kivisild, 1978). One offshore gas well was recently completed from a floating ice platform and a pipeline brought to shore. (Watts and Masterson, 1979, Palmer, Et. Al., 1979). Design and monitoring of these platforms have been carried out by FENCO CONSULTANTS LTD. of Calgary, Canada.

The platforms are designed so that maximum allowable elastic flexural stresses are not exceeded and also so that the creep deflections during drilling do not exceed the available freeboard of the ice platform. Stress calculations are conducted using theories applicable to elastic, homogeneous and isotropic plates on elastic foundations. Both closed form and finite element solutions are used (Masterson and Strandberg, 1978). These same methods have been used to predict creep deflections with considerable success and in this paper a method using the elastic formula and the exponental creep formula will be discussed. The formulation presents a rational method which can be easily extrapolated to predict long term deflections for different thickness and load cases.

KEY WORD	CLASSIFICATION
Utilizing Ice	Floating Platforms - Creep Analysis

SOURCE

Masterson, D.M.; Anderson, K. G.; Strandberg, A. G.
"Strain Measurements in Floating Ice Platforms and Their Application to Platform Design"
National Research Council of Canada, 1979

SUMMARY

The use of the natural ice cover in the Canadian high arctic for offshore petroleum exploration has made possible the drilling of 10 exploratory wells at very reasonable cost. The natural ice is thickened in the loaded area by flooding and freezing in thin layers and required ice thicknesses are obtained using theory for laterally loaded elastic, homogeneous plates on elastic foundations. The suitability of this type of theory, which assumes linear strain distribution through the section and a neutral axis at the middle plane, has been questioned, especially since the ice behaves as a visco-elastic axis material and creeps or strains with time.

Resistance strain gauges made of 3 m long 0.127 mm diameter Teflon-coated wire have been used the last two winters to measure strains in the ice platforms. They have worked well and during the winter and spring of 1978 strains at five different levels in an ice platform beneath the heavier loads were measured and recorded continuously for 62 days. Strain profiles were linear with the neutral axis 0.4 m above the middle plane of the 7.1 m thick platform. Maximum measured principal strains were 1300 and maximum extrapolated extreme fibre strains were 2100 confirming that the strains are small. Stress and effective elastic modulus values are shown to decrease rapidly in the early stages of loading.

KEY WORD	CLASSIFICATION
Utilizing Ice	Load Bearing Floating Systems - Platforms

SOURCE

Michel, B.; Drouin, M.; Lefebvre, L. M.; Rosenberg, P.; Murray, R.
"Ice Bridges of the James Bay Project"
Ice Mechanics Laboratory, Department of Civil Engineering, Laval University,
Quebec, Quebec, Canadian Geotechnical Journal, Vol. 11, No. 4, 1974

SUMMARY

In 1972 and 1973, a winter road crossing eight rivers was built in the James Bay territory to enable the installation of camps and the mobilization of all equipment, materials and fuel needed for the construction of a permanent road leading to the La Grande River. This paper reports on the bearing capacity theory, design, site selection, construction and testing of the ice bridges spanning the main rivers.

KEY WORD	CLASSIFICATION
Utilizing Ice	Ice Islands and Grounded Systems - Bridges

SOURCE

Nakawo, M.
"Criteria for Constructing Ice Platforms in Relation to Meteorological Variables"
Cold Regions Science and Technology, 6 (1983) 231-240

SUMMARY

A criterion for controlling the construction of an ice platform has been proposed in terms of constant heat deficit at a position near the surface of the builtup ice. Based on this criterion for construction and the relation between meteorological variables and the heat flux released from the surface towards the atmosphere, a time pericd for a single flooding-and-freezing cycle has been estimated. A chart has been constructed for this time period in relation to meteorological variables.

KEY WORD	CLASSIFICATION
Utilizing Ice	Ice Platforms

SOURCE

Nakawo, M.; Frederking, R.
"The Salinity of Artificial Built-Up Ice made by Successive Floodings of Sea Water"
Ottawa: National Research Council of Canada, Division of Building Research

SUMMARY

One method of thickening an ice sheet is "free flooding": ice is built up by successive flooding and freezing of sea water layers. The salinity of the built-up ice is of great interest because it plays an important role in establishing mechanical properties.

Detailed observations on salinity of flooded water and built-up ice were carried out during construction of an ice platform. Ice salinity was generally about 20% which is significantly lower than the salinity of the original sea water (30%). Almost half of the "lost salts" disappeared during the freezing period of a layer; the remainder were lost during subsequent floodings. Detailed salinity, thin section and dye migration measurements were used to postulate processes of horizontal as well as vertical desalination during construction of the ice platform.

KEY WORD	**CLASSIFICATION**
Utilizing Ice	Ice Platforms

SOURCE

Peters, D. B.; Ruser, J. R.; Watt, B. J.
"Rational Basis for Design of Floating Ice Roads and Platforms"
14th Annual OTC in Houston, Texas, May 3-6, 1982

SUMMARY

Floating ice roads and platforms have been used for several years in the Arctic. The standard design procedure is to select an ice thickness which will limit the maximum flexural tensile stress to an acceptable value. The theory of plates on elastic foundations is applied and it is usual to assume that the ice is uniform, homogeneous, and elastic.

The reality is far different since the ice behavior may be elastic, plastic, brittle, or viscoelastic, depending on a variety of factors such as age, strain rate, and temperature regime. In addition, it is necessary to allow for other load-inducing phenomena such as dynamically-induced gravity waves in the ice-water system and thermally-induced stresses.

The validity of the traditional method is reviewed in comparison with the field experience and analytical results using more realistic material models. A design method is proposed, based on the use of a limit state procedure. This method is considered more likely to provide reliable designs than procedures based purely on a working stress design procedure.

KEY WORD	**CLASSIFICATION**
Utilizing Ice	Ice Islands and Grounded Systems - Roads and Platforms

SOURCE

Potter, R. E.; Walden, J. T.; Haspel, R. A.
"Design and Construction of Sea Ice Roads in the Alaskan Beaufort Sea"
Thirteenth Annual Offshore Technology Conference 1981, proceedings - Dallas: Offshore Technology Conference, 1981

SUMMARY

To service offshore drill sites in the Alaskan Beaufort Sea, Sohio Petroleum Company has constructed a network of floating sea ice roads during the early winters of 1978-79 and 1980-81. Such construction involves the grading and leveling of bottom-founded ice in nearshore regions, and the pumping of thin layers of underlying seawater onto floating ice to augment the natural buildup rate. The floating roads, which have had lengths of up to 9 much as 200 tons. Ice thicknesses exceeding 6 ft (5 ft artificially grown) are needed to provide an adequate foundation. This discussion principally focuses on the planning, design, construction and maintenance associated with floating ice road surfaces. ...The paper is intended as a compilation of Sohio's operational experiences, assembled into an overview of the factors and elements to be integrated in an offshore ice road program.

KEY WORD	CLASSIFICATION
Utilizing Ice	Load Bearing Floating Systems - Roads

SOURCE

Shell Oil Company
"Design and Analysis of Ice Roads"

SUMMARY

This report describes a study to develop design information for an ice road and ice working platform for a site in the southern Beaufort Sea. Analytical procedures are described and the design variables are discussed in terms of their effect on the resulting design. The primary effort involved in an ice road design is the selection of the design thickness. The controlling design condition for design of an ice road is generally the bearing capacity. In some cases, long-term deflections may govern the design ice thickness.

KEY WORD	CLASSIFICATION
Utilizing ice	Roads

RESPONSES TO THE ICE ENVIRONMENT

3.2 ICE-RESISTANT SCHEMES

LIST OF TECHNICAL PUBLICATIONS

RESPONSES TO THE ARCTIC ENVIRONMENT - ICE RESISTANT SCHEMES

Title	Author	Publication	Publication Date	Page No.
Slope Protection for Artificial Island	Czerniak, M. T. Collins, J. I. Shak, A. T.	Ocean Industry, 16(1981)8, August	1981	241
Ice Forces on Old and New Offshore Lighthouses in St. Lawrence Waterways	Danys, J. V.	POAC	1977	242
Structural Design Consideration in the Marine Environment	Gaythwaite, J. W.	J. Boston Soc. Civ. Eng. Sect. ASCE, 65(1978)3	1978	243
Survey of Design Criteria for Harbors and Channels in Cold Regions	Haynes, F. Donald	US Army Cold Reg. Res. & Eng. Lab Hanover, NH CRREL Rep n 76-3	1976	244
Ice Design Statistics for the Canadian Beaufort Sea	Marcellus, R. W. Morrison, T. B.	Canadian Marine Engineering Ltd., Dome Petroleum Limited, Gulf Canada Resources Inc., Esso Resources Canada Limited, Canadian Marine Engineering Ltd.	1982	245
Ice Force Design Considerations for Conical Offshore Structures	Ralston, T. D.	In: POAC 77, 4th Int. Conf. Port and Ocean Eng. under Arctic Cond., Mem. Univ. Newfoundland, St. John's, Sept. 26-30, 1977, St. John's, Ocean Eng. Inf. Centre, 1978, Vol. 2	1978	246

LIST OF TECHNICAL PUBLICATIONS

RESPONSES TO THE ARCTIC ENVIRONMENT - ICE RESISTANT SCHEMES

Title	Author	Publication	Publication Date	Page No.
Design of Harbor Structures for Boats	Wortley, C. Allen	POAC 79, International Conference on Port and Ocean Engineering Under Arctic Conditions, 5th, Proc, University of Trondheim, Norw. Inst. of Technology, August 13-18, 1979, Vol. 2. Published by University of Trondheim, Norw. Inst. of Technology	1979	247

SOURCE

Czerniak, M. T.; Collins, J. I.; Shak, A. T.
"Slope Protection for Artificial Island"
Ocean Industry, 16(1981)8, August

SUMMARY

A research project entitled "Slope Protection Design Developed for Beaufort Sea Islands" is presented. The article describes the weather conditions in this area both in ice-free season and ice season, construction constraints and slope protection considerations. The project includes wave and ice model tests.

KEY WORD	CLASSIFICATION
Ice Resistant Schemes	Slope Protection

SOURCE

Danys, J.V.
"Ice Forces on Old and New Offshore Lighthouses in
the St. Lawrence Waterway"
In: POAC 77, 4th Int. Conf. Port and Ocean Eng.
under Arctic Cond., Mem. Univ. Newfoundland, St.
Johns, Sept. 26-30, 1977, St. Johns, Ocean Eng.
Inf. Centre, 1978, Vol. 1

SUMMARY

At present, theoretical formulae, laboratory testing of small samples, model testing with artificial or natural ice, or mathematical models are not producing reliable results for a practical design as yet. Analysis of old and new structures exposed to ice thrust provides valuable information about actual ice forces, especially in cases where complete or partial failures occurred. In this paper, stability and some failures of sixty-nine old and new lighthouses and lightpiers are analyzed. The results of this analysis are summarized in three tables.

KEY WORD	CLASSIFICATION
Ice Resistant Schemes	Cone-shaped structures

SOURCE

Gaythwaite, J. W.
"Structural Design Consideration in the Marine Environment"
J. Boston Soc. Civ. Eng. Sect. ASCE, 65(1978)3

SUMMARY

Various factors peculiar to the marine environment, affecting structural design, have been discussed. All of these factors should be considered for their potential effect, although they ultimately may not affect a given structure. The ocean environment is one in which environmental loadings must be more carefully investigated than on land-based structures and is an environment in which materials generally deteriorate much more quickly, wind, waves, currents, ice, hydrostatic pressure, and impact are the primary sources of loadings a structure must contend with, while it must also stand up to deteriorating agents such as corrosion, attack by marine organisms, wear and fatigue.

KEY WORD	CLASSIFICATION
Ice Resistant Schemes	Structural Design

SOURCE

Haynes, F. Donald
"Survey of Design Criteria for Harbors and Channels in Cold Regions"
US Army Cold Reg. Res. & Eng. Lab, Hanover, NH
CRREL Rep. n 76-3 March 1976 36 p

SUMMARY

A world-wide review of the literature applicable to the design of harbors and channels in cold regions was conducted. Forces due to ice movement present the dominant factor in the design of marine structures in cold regions. Expressions for calculating the ice force are presented. Other factors related to design criteria such as construction materials, structure geometry and methods of ice suppression are discussed. 87 refs.

KEY WORD	CLASSIFICATION
Ice Resistant Schemes	Design

SOURCE

Marcellus, R. W.; Morrison, T. B.
"Ice Design Statistics for the Canadian Beaufort Sea"
Canadian Marine Engineering Ltd.
Dome Petroleum Limited
Gulf Canada Resources Inc.
Esso Resources Canada Limited
Canadian Marine Engineering Ltd.
1982

SUMMARY

...This report is a companion report to two further CMEL reports dealing with an ice/structure interaction computer model and probabilistic ice loads on offshore structures in the Beaufort Sea. ...The intent of these reports is to collectively provide a preliminary probabilistic assessment of the global ice loads which may be applied to offshore production structures located on the Beaufort Sea Continental Shelf. These reports were initiated to demonstrate the feasibility of constructing structures to resist the ice loads in this area; they do not contain sufficient information for detailed design. ...The ice statistics contained in this report are representative of the Canadian Beaufort Sea and have been used in the computer interaction model to predict return period global ice loads on offshore production structures. ...Offshore structures ... will be subjected to interactions with large ice features. A number of interaction scenarios are possible. These involve impacts by multi-year floes, multi-year hummock low. ...This report concentrates on the larger ice features such as multi-year floes which may interact with fixed offshore structures in the region. A summary of the report is presented in Chapter 2.

KEY WORD	CLASSIFICATION
Ice Resistant Schemes	Models

SOURCE

Ralston, T. D.
"Ice Force Design Considerations for Conical Offshore Structures"
In: POAC 77, 4th Int. Conf. Port and Ocean Engineering
under Arctic Cond., Mem. Univ. Newfoundland, St. John's,
September 26-30, 1977, St. John's, Ocean Eng. Inf. Centre,
1978, Vol. 2

SUMMARY

Analytical and model basin studies of sheet ice failure against conical structures have been previously discussed in the literature. The analytical work was based on a linear elastic description of ice deformation, with a brittle failure criterion, and was found to underestimate the model basin data. A new analysis has been developed that considers a floating ice sheet to be an elastic-plastic plate resting on an elastic-plastic foundation. The upper bound procedure of plastic limit analysis leads to a mathematical model for both sheet ice failure and rideup on a conical structure.

KEY WORD	CLASSIFICATION
Ice Resistant Schemes	Conical Structures

SOURCE

Wortley, C. Allen
"Design of Harbor Structures for Boats"
POAC 79, International Conference on Port and Ocean Engineering Under Arctic Conditions, 5th, Proc, University of Trondheim, Norw Inst. of Technology, August 13-18, 1979, Vol. 2.
Published by University of Trondheim, Norw Inst. of Technology 1979

SUMMARY

Design recommendations for fixed and floating boat harbor structures in northern climates are presented. These recommendations include estimates of stationary and moving horizontal and vertical ice forces on boat harbor structures. Additionally, methods to proportion and position structures, and methods to suppress and melt ice are recommended. These methods minimize or eliminate the adverse effects of ice. Information obtained from extended winter observations in two hundred northern harbors, on ice thicknesses, water temperatures, ice cracking patterns, ice collars on pilings, rubble ice accumulations, and damages is also given.

KEY WORD	CLASSIFICATION
Ice Resistant Schemes	Fixed and Floating Boat Harbors

RESPONSES TO THE ARCTIC ENVIRONMENT

3.3 ICE CONTROL

LIST OF TECHNICAL PUBLICATIONS

ICE CONTROL

Title	Author	Publication	Publication Date	Page No.
Protection of Hydraulic Structures from Icing	Aleinikov, S. M. Lyapin, B. E. Zhidkikh, M. I. (et al)	In: Proc. IAHR Int. Symp. on Ice, Quebec, July 27-31, 1981, Quebec, Univ. Laval, 1981, Vol. II	1981	248
Concepts for Ice Management at Arctic LNG Terminal	Cammaert, A. B. Miller, D. R. Gill, R. J.	Acres Consult Serv Ltd., Can, POAC '79, Int. Conf. on Port and Ocean Eng under Arctic Cond, 5th, Proc, Univ. of Trondheim, Norw Inst of Technol, Aug 13-18, 1979 Vol. 2 Publ. by Univ. of Trondheim, Norw Inst of Technol	1979	249
Methods of Ice Control for Arctic Production Structures	Cammaert, A. B. Gill, R. J.	Acres Consult Serv Ltd., Can, Presented: Seminar/Workshop on Sea Ice Management, Memorial University of Newfoundland, St. John's, November 15-18, 1983	1983	250
Icebreakers and Icebreaking (Citations from the NTIS Data Base)	Habercom, G. E., Jr.	NTIS, Springfield, VA Publ. by NTIS	1978	251
Development of Field Testing of a Beaufort Sea Ice Boom	Potter, R. E. Reid, D. L. Bruce, J. C. Noble, P. G.	Fourteenth Annual Offshore Technology Conference in Houston, Texas, May 3-6, 1982	1982	252

SOURCE

Aleinkov, S. M.; Lyapin, B. E.; Zhidkikh, M. I. (et al)
"Protection of Hydraulic Structures from Icing"
In: Proc. IAHR Int. Symp. on Ice, Quebec, July 27-31,
1981, Quebec, Univ. Laval, 1981, Vol. II

SUMMARY

The icing of hydraulic structures looked upon as a surface process resulting from collision of water drops with the structure surface followed by their spreading and freezing in the form of ice knots. Both active and passive de-icing techniques are described. The ice adhesion to the structure materials and the effect of various factors on its strength are discussed. On the basis of laboratory, field and theoretical investigations an integrated system designed to facilitate the operation of gates in extended navigation conditions has been developed.

KEY WORD	CLASSIFICATION
Ice Control-Ice Suppression	Hydraulic Structures Protection

SOURCE

Cammaert, A. B.; Miller, D. R.; Gill, R. J.
"Concepts for Ice Management at Arctic LNG Terminal"
Acres Conlt Serv Ltd., Can
POAC 79, Int. Conf. on Port and Ocean Eng. Under Arctic Cond.,
5th, Proc, Univ. of Trondheim, Norw Inst of Technol, Aug
13-18 1979 Vol. 2. Publ. by Univ of Trondheim, Norw Inst
of Technol, 1979

SUMMARY

As part of the LNG transportation system for the field located on the Sabine Peninsula of Melville Island in Canada, it is proposed to construct a marine terminal at the nearest suitable harbor on the island M-Bridport Inlet which opens into Viscount Melville Sound. Concern is shown for ice management problems anticipated for the terminal area, since the natural ice growth averages 2 m. An analysis of the accelerated ice growth caused by repeated ship passages shows that ice thickness can be as much as 6 m at the end of a normal winter. A comprehensive review on potential ice management techniques is summarized. The technical and economic feasibility of each of the potential solutions is discussed. From these preliminary investigations, it is concluded the use of waste heat in the form of a thermal discharge from the liquefaction process is the most effective and reliable way to inhibit ice accumulation near the terminal.

KEY WORD	CLASSIFICATION
Ice Control - General	Ice Management Concept

SOURCE

Cammaert, A. B.; Gill, R. J.
"Methods of Ice Control for Arctic Production Structures"
Acres Conlt Serv Ltd., Can
Presented: Seminar/Workshop on Sea Ice Management, Memorial University of Newfoundland, St. John's, November 15-18, 1983

SUMMARY

This paper addresses ice control problems which may interfere with ship movements specific to permanent production facilities. While research and experimentation efforts have been applied to ice control problems associated with existing artificial islands and drillships, these solutions cannot easily by extrapolated to fixed gravity structures or artificial islands. The requirement for year round drilling in heavy ice conditions, repeated passage of ships in landfast ice and ice interaction with fixed installations all combine to provide ice control problems experienced more commonly in Arctic ports and harbours.

Upon identification and discussion of ice control problems associated with gravity-base structures and artificial islands, potential control techniques are offered by the authors. Conclusions concerning the best technique for a specific problem are not drawn, but rather criteria are established and presented for the evaluation of these techniques. On the basis of such factors as effectiveness, availability of energy source, environmental impact, operational limits, costs, reliability and safety, control techniques can be assessed.

KEY WORD	CLASSIFICATION
Ice Control - General	Structures

SOURCE

Habercom, G. E., Jr.
"Icebreakers and Icebreaking (Citations from the NTIS Data Base)"
NTIS, Springfield, VA
Publ. by NTIS
Dec. 1978

SUMMARY

The design and performance of icebreakers, icebreaking, ice navigation and ice distribution are reviewed in these Government-sponsored research reports. This updated bibliography was prepared by searching the 1964-November 1978 data base of NTIS. It contains 213 abstracts, 10 of which are new entries to the previous edition.

KEY WORD	CLASSIFICATION
Ice Control - Ice Breaking	Design and Performance

SOURCE

Potter, R. E.; Reid, D. L.; Bruce, J. C.; Noble, P. G.
"Development and Field Testing of a Beaufort Sea Ice Boom"
Fourteenth Annual Offshore Technology Conference in Houston, Texas,
May 3-6, 1982

SUMMARY

A description of the conceptual development, full-scale field testing in the Beaufort Sea and model testing of an experimental Ice Boom envisioned for application in the Beaufort Sea. The concept of artificially generating a grounded rubble pile in Beaufort Sea open water areas using a relatively cheap "trigger mechanism", if successfully proven, could have numerous applications in support of offshore petroleum operations.

KEY WORD	CLASSIFICATION
Ice Control - General	Ice Boom Tests

4.0 EXISTING REGULATIONS AND GUIDELINES

LIST OF TECHNICAL PUBLICATIONS

EXISTING REGULATIONS

Title	Author	Publication	Publication Date	Page No.
Design Aspects of a Mobile Arctic Caisson	Bruce, J. C. Harrington, A. G.	Fourteenth Annual Offshore Technology Conference in Houston, Texas, May 3-6, 1982	1982	253
Selection of Local Design Ice Pressures for Arctic Systems	Bruen, F. J. Byrd, R. C. Vivatrat, R. C. Watt, B. J.	Fourteenth Annual Offshore Technology Conference in Houston, Texas, May 3-6, 1982	1982	254
Review of Steels Used in the Construction of Offshore Structures	Eide, G. H. Vilpponen, K. O.	Department of Energy, Mines and Resources of Canada/Canment, Report No. 82-0086, April 30, 1982	1982	255
Testing Methods of Ice	Frederking, R. Gavrilo, V. P. Goodman, D. J. Hausler, F. U. Hirayama, K. Kry, P. R. Mellor, M. Petrov, I. G. Tryde, P. Vaudrey, K.	IAHR - 3rd Report of Working Group on Testing Methods in Ice	1981	256
Studies Supporting Update of the CASPP Regulations Group I and II - Final Report	Glen, I. Daley, C. Edworthy, J. Gareau, G.	Arctec Canada Limited, FR 586A, Contract No. OST 79 00065, DSS File No. 19St.T8275-9-0082	1982	257

LIST OF TECHNICAL PUBLICATIONS

EXISTING REGULATIONS

Title	Author	Publication	Publication Date	Page No.
Existing Ice Codes and Suggested Criteria	Kivisild, H. R. Iyer, S. H.	Proceedings - IAHR Symposium on Ice Problems, 5th, Lulea, Sweden, 7-9 August, 1978. Lulea, Sweden, International Association of Hydraulic Research, 1978	1978	258
Dynamic Ice Forces and Piers and Piles, an Assessment of Design Guidelines in the Light of Recent Research	Neill, Ch. R.	Canadian Journal Civil Engineering, 3(1976)2	1976	259
Ice Force Design Considerations for Conical Offshore Structures	Ralston, T. D.	Exxon Production Research Company, Houston, Texas 77001		260
Standardized Testing Methods for Measuring Mechanical Properties of Ice	Schwarz, J. Frederking, R. Gavrillo, V. Petrov, I. G. Hirayama, K. I. Mellor, M. Tryde, P. Vaudrey, K. D.	Cold Regions Science and Technology, 4(1981)245-253	1981	261
SNIP-II-57-75 Construction Standards and Rules, Part II Design Standards Chapter 57: Loads Exerted on Hydraulic Structures by Waves, Ice and Ships	Sinclair, D. A.	Ottawa: National Research Council of Canada	1980	262

LIST OF TECHNICAL PUBLICATIONS

EXISTING REGULATIONS

Title	Author	Publication	Publication Date	Page No.
Instruction for Determining Ice Loads on River Structures	State Committee of the Council of Ministers (USSR) for Construction (Gosstroi, USSR)	Ottawa: National Research Council of Canada, TT-1663, 1973	1973	263
Ice Engineering Design of Marine Piling and Piers	Wortley, C. A.	Proc. ASCE, J. Tech. Councils, 108(1982)TC2, Nov. Paper No. 17491	1982	264

SOURCE

Bruce, J. C.; Harrington, A. G.
"Design Aspects of a Mobile Arctic Caisson"
Fourteenth Annual Offshore Technology Conference in Houston, Texas
May 3-6, 1982

SUMMARY

This paper describes the main features of a bottom founded mobile arctic structure which will have the capability of year round operation in a variety of ice conditions in water depths ranging from some 15 to 40 metres. The caisson is essentially a continuous steel annulus supporting a deck carrying drilling and top side facilities. The core of the annulus will be filled with sand to provide most of the resistance to horizontal ice loading. A feature of the design is that means are incorporated for keeping the ballast water, and the sand core, in an unfrozen state throughout the winter.

KEY WORD	CLASSIFICATION
Existing Regulations	Mobile Arctic Structure Design

SOURCE

Bruen, F. J.; Byrd, R. C.; Vivatrat, V.; Watt, B. J.
"Selection of Local Design Ice Pressures for Arctic Systems"
Fourteenth Annual Offshore Technology Conference in Houston, Texas
May 3-6, 1982

SUMMARY

Most ice mechanics research for arctic structures has been devoted to predictions of the maximum design ice force in global terms. It is now being recognized that the local pressure between the ice feature and the structure is also a very important design variable. Local design considerations can govern the design of either steel or concrete arctic structures.

Methods for selecting appropriate design pressures are reviewed. These include Hertzian contact theory, plasticity theory, field observations and the empirical procedures incorporated in ice-strengthened vessel design codes. The results show a wide scatter in possible local ice pressures. The importance of scale is discussed, particularly in the case of brittle ice behavior. Finally, procedures are recommended for selecting design pressures. Consideration is given to first year and multiyear ice features.

KEY WORD	CLASSIFICATION
Existing Regulations	Local Design Ice Pressures

SOURCE

Eide, G. H.; Vilpponen, K. O.; et. al.
"Review of Steels Used in the Construction of Offshore Structures"
Department of Energy, Mines and Resources of Canada/Canmet,
Report No. 82-0086, April 30, 1982

SUMMARY

This report reviews material requirements to structural steels and weldments in mobile and fixed offshore platforms. The review is based on regulatory guidelines set forth by U.S. Geological Surveys, The Norwegian Petroleum Directorate, The Department of Energy UK, as well as on rules issued by the Classification Societies (DnV, Lloyds Register, ABS, Bureau Veritas, Germanische Lloyds). These guidelines and rules are compared with current offshore practice as reflected by APT recommendations and owners specifications. Application of these requirements to Arctic environment is commented upon.

KEY WORD	CLASSIFICATION
Existing Regulations	Structural Steel Requirements

SOURCE

Frederking, R.; Gavrilo, V. P.; Goodman, D. J.; Hausler, F. U.; Hirayama, K.; Kry, P. R.; Mellor, M.; Petrov, I. G.; Tryde, P.; Vaudrey, K.
"Testing Methods of Ice"
IAHR - 3rd Report of Working Group on Testing Methods in Ice

SUMMARY

Two reports have been presented by this Working Group. The first was published in the Proceedings of the 3rd International Symposium on Ice Problems, 1975 (1) and focused on methods of carrying out uniaxial tension and compression tests. The second was published following the 4th International Symposium on Ice Problems (2) and concentrated on flexural testing with in situ cantilever beams, strain measurements in ice, an update on compression testing, and some initial thoughts on brine drainage and friction measurements. The two reports have been integrated in a recently published journal paper (3).

The Working Group met at Trondheim in 1979 in connection with POAC and in Quebec in 1981 at the IAHR Ice Symposium. The present report offers new recommendations on multiaxial testing and friction measurements, a test data sheet, and some initial observations on the influence of air content and machine stiffness on strength.

KEY WORD	CLASSIFICATION
Existing Regulations	Testing Methods of Ice

SOURCE

Glen, I.; Daley, C.; Edworthy, J.; Gareau, G.
"Studies Supporting Update of the CASPP Regulations Group I and II - Final Report"
Arctec Canada Limited, FR 586A, Contract No. OST 79 00065, DSS File No. 19ST.T8275-9-0082

SUMMARY

The work being presented centers around the examination of a proposal for setting design loads for Arctic vessels published by Johansson et al (4). The stated philosophy behind the Johansson approach is to design ships for the "worst possible ice scenario". The worst scenario was considered to be a head-on ram of glacial or multi-year ice at speed.

The questions addressed herein are therefore:

- o What is the likelihood of striking glacial or multi-year ice (or other hazardous ice features)?
- o Given that an ice impact occurs, is Johansson's approach to the determination of pressures, forces and areas sound?
- o Given that the pressures, forces and areas can be determined, what is the effect on local structure and on the hull girder?

The first question is dealt with in Sections 2 and 3, the second in Section 4 and the third in Sections 5 and 6. An overview, in the form of a probability network shows the interrelation of all aspects of ship/ice interaction (Figure S.1). The results are summarized in the following pages.

KEY WORD	CLASSIFICATION
Existing Regulations	Ship/Ice Interaction

SOURCE

Kivisild, H. R.; Iyer, S. H.
"Existing Ice Codes and Suggested Criteria"
Proceedings - IAHR Symposium on Ice Problems, 5th, Lulea, Sweden,
7-9 August, 1978. Lulea, Sweden, International Association of Hydraulic
Research, 1978
These guidelines reflect inhouse sources of information gathered by FENCO

SUMMARY

...The purpose of this paper is to briefly review the existing codes and design practices, point out their limitations and develop a new set of guidelines on a rational basis ... In establishing these guidelines, reference has been made to the inhouse sources of information gathered from the ice-related projects carried out by FENCO over a period of years as well as a critical review of the published information of others. ...

KEY WORD	CLASSIFICATION
Existing Regulations	Existing Ice Codes and Suggested Criteria

SOURCE

Neill, Ch. R.
"Dynamic Ice Forces on Piers and Piles, an Assessment of Design Guidelines in the Light of Recent Research"
Canadian Journal Civil Engineering, 3(1976)2

SUMMARY

The first part of the paper reviews and assesses various analytical approaches and design formulas used to estimate forces due to the impact of moving ice on piles, piers and towers. The application of dimensional analysis to the problem is outlined briefly. The second part reviews and assesses fullscale data available from research and from report evaluations of structure performance, and attempts to summarize their more significant findings. The third part reviews a number of recent small-scale laboratory investigations. Finally, suggestions are made for improvement of current design guidelines and practices.

KEY WORD	CLASSIFICATION
Existing Regulations	Ice Force Design Considerations

SOURCE

Ralston, T. D.
"Ice Force Design Considerations for Conical Offshore Structures"
Exxon Production Research Company, Houston, Texas 77001

SUMMARY

Arctic offshore structures may be exposed to a variety of ice features including sheet ice, unconsolidated ridges, ice rubble fields, and consolidated multiyear ridges. The interaction of these ice features with conical structures is the subject of investigations that consist of a combination of model tests and analytical studies.

Analytical and model basin studies of sheet ice failure against conical structures have been previously discussed in the literature. The analytical work was based on a linear elastic description of ice deformation, with a brittle failure criterion, and was found to underestimate the model basin data. A new analysis has been developed that considers a floating ice sheet to be an elastic-plastic plate resting on an elastic-plastic foundation. The upper bound procedure of plastic limit analysis leads to a mathematical model for both sheet ice failure and rideup on a conical structure. This description includes the effects of cone angle, waterline diameter, exposed conical surface, ice/structure friction, ice flexural strength, and ice sheet thickness. This model compares favorably with previously published model test data and can be viewed as a possible alternative to empirical models adapted to such data. If average ice flexural strength and sheet thickness values are used to determine the plastic moment capacity and weight of the ice sheet, the upper bound solution presented in this paper is in agreement with the average force peaks reported for the model tests.

Multiyear ridges are an important design consideration for offshore structures in the deeper waters of the Beaufort Sea. The forces required to break these ridges have been estimated using published theories that approximate the ridge as a beam on an elastic foundation. This approach implies that short, rather than long, multiyear ridges may impose the greatest ice forces on structures that are designed to fail ice in flexure. There is a need for confirmation with model tests and perhaps the development of nonlinear analytical models.

KEY WORD	CLASSIFICATION
Existing Regulations	Ice Force Design Considerations

SOURCE

Schwarz, J.; Frederking, R.; Gavrillo, V.; Petrov, I. G.; Hirayama, K. I.; Mellor, M.; Tryde, P.; Vaudrey, K. D.
"Standardized Testing Methods for Measuring Mechanical Properties of Ice"
Cold Regions Science and Technology, 4(1981)245-253

SUMMARY

The results of nominally similar test vary greatly due to the fact that almost every ice research group uses different testing methods. This is of course a hindrance to the Ice Engineering field. In order to improve the quality, comparability and usefulness of the test data resulting from mechanical property investigations, the IAHR Section On Ice Problems considers it necessary to standardize ice testing methods. Herewith the Working Group of the IAHR Section on Ice Problems proposes its recommendation for "Standardized Testing Methods for Measuring Mechanical Properties of Ice". It should be noted that the suggested recommendations remain open to revision as the development of ice testing methods progresses.

KEY WORD	CLASSIFICATION
Existing Regulations	Ice Testing Methods

SOURCE

Sinclair, D. A.
"SNIP-II-57-75 Construction Standards and Rules, Part II Design Standards, Chapter 57: Loads Exerted on Hydraulic Structures by Waves, Ice and Ships"
Ottawa: National Research Council of Canada, 1980

SUMMARY

Canada and the Soviet Union share ... similar problems with ice loads on structures. Soviet experience in dealing with ice problems has resulted in the publication of ice codes in 1959, 1967 and now most recently in 1976. There are now efforts in Canada to revise and update existing ice codes here. It was felt that the translation of this most recent Soviet Code would be a useful contribution to Canadian engineers and code writers. Only the part on ice of a chapter in SNIP-II-57-75 ... has been translated and printed in the publication. ...

KEY WORD	CLASSIFICATION
Existing Regulations	Ice Codes

SOURCE

State Committee of the Council of Ministers (USSR) for Construction
(Gosstroi, USSR)
"Instruction for Determining Ice Loads on River Structures"
Ottawa: National Research Council of Canada, TT-1663, 1973

SUMMARY

The "Instructions for Determining Ice Loads on River Structures" (Building Standard 76-66) were formulated by the B. E. Vedeneev All Union Research Institute of Hydrological Engineering, Ministry of Power and Electrification, USSR, in conjunction with the Novosibirsk Engineering Institute for Railroad Transport, Ministry of Communication; VNII VODGEO (All Union Research Institute for Water Supply, Hydrological Engineering Structures and Engineering Hydrogeology) Gosstroi, USSR; and the State Hydrological Institute, Main Administration of the Hydrometeorological Service, Council of Ministers, USSR.

When these "Instructions" come into force on October 1, 1967 they replace the "Technical Specifications for determining ice loads on river structures" (SN 76-59).

KEY WORD	CLASSIFICATION
Existing Regulations	Ice Loads on River Structures

SOURCE

Wortley, C. A.
"Ice Engineering Design of Marine Piling and Piers"
Proc. ASCE, J. Tech. Councils, 108(1982)TC2, Nov. Paper
No. 17491

SUMMARY

Design criteria and structure designs for pilings, piers, and docks subject to ice are presented. Included are estimates of stationary and moving horizontal and vertical ice forces, types of constructions and materials, facility layouts to mitigate ice problems, and methods of ice suppression. Design recommendations are based on actual design experiences, field investigations in several hundred U.S. and Canadian Great Lakes harbors and ports over a period of years, and laboratory studies.

KEY WORD	CLASSIFICATION
Existing Regulations	Design Criteria of Structures

5.0 DESIGN GUIDELINES

LIST OF TECHNICAL PUBLICATIONS

DESIGN GUIDELINES

Abbreviations: POAC = Proceedings of Port and Ocean Engineering under Arctic Conditions

ASCE = American Society of Civil Engineers

M.I.T. = Arctic Technology and Policy = Proceedings of the Second Annual M.I.T. Sea Grant College Program Lecture and Seminar Edited by Ira Dyer and Chryssostomos Chryssostomias, Massachusetts Institute of Technology.

CRREL = Cold Regions Research and Engineering Laboratory, Hanover N.H.

LIST OF TECHNICAL PUBLICATIONS

DESIGN GUIDELINES

Title	Author	Publication	Publication Date	Page No.
Protection of Hydraulic Structures from Icing	Aleinikov, S. M. Lyapin, B. E. Zhidkikh, M. I. (et al)	In: Proc. IAHR Int. Symp. on Ice, Quebec, July 27-31, 1981, Quebec, Univ. Laval, 1981, Vol. II	1981	265
Probabilistic Ice-Structure Interaction Theory	Bercha, F. G. Danys, J. V. Rokne, J. G.	In: Proc. IAHR Symp. on Ice Problems, Luleaa (Sweden), Aug. 1978, Luleaa, Int. Assoc. Hydraul. Res., Section for Ice Problems, 1978, Part I, Ice Forces on Structures	1978	266
A Steel Production Structure for the Alaskan Beaufort Sea	Boaz, I. B. Bhula, D. N.	13th Annu Spe of AIME et al Offshore Tech (5/4-7/81) Proc. V. 3	1981	267
"Design Criteria for Nearshore & Offshore Structures"	Brunn, Per Moe, Geir	POAC '81	1982	268
"Impact of Large Ice Floes and Icebergs on Marine Structures"	Cammaert, A.B. Tzinker, G.P.	POAC '81	1982	269
"Design Factors for Rubble Mound Structures under Ice and Wave Attack"	Czerniak, Martin T. Shak, Arthur T. Collins, J. Ian	POAC '81	1982	270
Slope Protection for Artificial Island	Czerniak, M. T. Collins, J. I. Shak, A. T.	Ocean Industry, 16(1981)8, Aug.	1981	271

LIST OF TECHNICAL PUBLICATIONS

DESIGN GUIDELINES

Title	Author	Publication	Publication Date	Page No.
"Design of Wharves for Winter Navigation in St. Lawrence River"	Déry, Jacques L.	POAC '81	1982	272
The Ship Ice Interaction	Enkvist, E. Varsta, P. Riska, K.	In: POAC 79, 5th Int. Conf. Port and Ocean Eng. under Arctic Conditions, Norw. Inst. Technol., 1979, Trondheim, Univ. Trondheim, 1979, Procs. Vol. II	1979	273
Structural Design Consideration in the Marine Environment	Gaythwaite, J. W.	J. Boston Soc. Civ. Eng. Sect. ASCE, 65(1978)3	1978	274
"River and Lake Ice Processes Relevant to Ice Loads"	Gerard, Robert	ASCE 1983-Design for Ice Forces	1983	275
"Concrete Structures for the Arctic"	Gerwick, Jr. Ben C.	M.I.T. - Arctic Technology & Policy	1983	276
"Survey of Design Criteria for Harbours and Channels in Cold Regions"	Haynes, F. Donald	CRREL Report No. CRREL-76-3	1976	277
"Risk Assessment of Offshore Structures - Experience and Principles"	Holand, Ivar Moan, Torgier	POAC '81	1982	278
"Risk & Safety Assessment for Arctic Offshore Projects"	Jordan, Ian J.	M.I.T. - Arctic Technology & Policy	1983	279
"Marine Foundations"	Kivisild, Hans R.	POAC '81	1982	280

LIST OF TECHNICAL PUBLICATIONS

DESIGN GUIDELINES

Title	Author	Publication	Publication Date	Page No.
"Arctic Terminal for Ice Breaking Tankers Study"	Lewis, P.E.	Office of Port and Intermodel Development Maritime Administration, Washington, D.C. Report No. Job-12963: MA-970-79049	1979	281
"Design of Navigational Structures for Ice Forces"	Maatanen, Mauri	ASCE - Design for Ice Forces	1983	282
"Design of Manmade Offshore Islands for Ice Forces"	Machemehl, Jerry L.	ASCE - Design for Ice Forces	1983	283
"Artificial Islands and Steel Structures in the Beaufort Sea"	Maxwell, D. McGonigal, D. Graham, C.	M.I.T. - Arctic Technology and Policy	1983	284
"Cold Regions Science and Engineering Monograms 3"	Michel, Bernard	CRREL - Report No. CRREL-CRSE-3-BLB	1970	285
Heat Exchange at Surface of Built-Up Ice Platform During Construction	Nakawo, M.	Cold Regions Science and Technology, V. 3, No. 4	1980	286
Dynamic Ice Forces on Piers and Piles, an Assessment of Design Guidelines in the Light of Recent Research	Neill, Ch. R.	Can. J. Civil Eng., 3(1976)2	1983	287
"Design of Bridges for Ice Forces"	Neill, Charles R.	ASCE - Design for Ice Forces	1983	288
"Design of Submerged & Floating Structures for Ice Forces"	Noble, Peter G.	ASCE - Design for Ice Forces	1983	289

LIST OF TECHNICAL PUBLICATIONS

DESIGN GUIDELINES

Title	Author	Publication	Publication Date	Page No.
"Design of Port and Coastal Structures for Ice Forces"	Nottingham, Dennis Drage, Brent T.	ASCE - Design for Ice Forces	1983	290
"Upper Bounds of Ridge Pressure on Structures"	Prodanovic, Anton	POAC '81	1982	291
"General Cargo Marine Terminal Frobisher Bay, NWT - Preliminary Engineering Report"	Public Works Canada, Western Region	Public Works Canada Ottawa, Ontario	1980	292
Ice Force Design Considerations for Conical Offshore Structures	Ralston, T. D.	In: POAC 77, 4th Int. Conf. Port and Ocean Eng. under Arctic Cond., Mem. Univ. Newfoundland, St. Johns, Sept. 26-30, 1977, St. Johns, Ocean Eng. Inf. Centre, 1978, Vol. 2	1978	293
Techniques for the Study of the Structure Interaction	Robbins, R.J. Verity, P.H. Taylor, T.P. Metge, M.	POAC	1976	294
"Failure Modes and Forces of Pressure Ridges Acting or Cylinderical Towers"	Rojansky, M. Gerwick, B.C.	POAC '81	1982	295
"Ice Effects on Planning, Design and Operation of a Major Oil Terminal"	Saunders, T.F. Timascheff, M.	Proceedings of 23rd International Navigation Congress, Ottawa 1973	1973	296
"Cold Region Canadian Port Development"	Saunders, T.F.	3rd International Ocean Development Conference - Tokyo, Japan 1975	1975	297

LIST OF TECHNICAL PUBLICATIONS

DESIGN GUIDELINES

Title	Author	Publication	Publication Date	Page No.
SNIP-II-57-75 Construction Standards and Rules, Part II Design Standards, Chapter 57: Loads Exerted on Hydraulic Structures by Waves, Ice and Ships	Sinclair, D. A.	Ottawa: National Research Council	1980	298
Selection of Design Ice Pressures and Application to Impact Load Prediction	Slomski, S. Vivatrat, V.	In: POAC 83, Proc. 7th Int. Conf. on Port and Ocean Eng. under Arctic Conditions, Helsinki, April 1983, Espoo, VTT	1983	299
"Measurement of Ice Forces on Structures"	Sodhi, D.S. Haynes, F.D.	ASCE - Design for Ice Forces	1983	300
"Design of Offshore Pipelines for Ice Environment"	Timmermans, W.J.	ASCE - Design for Ice Forces	1983	301
"Steel Selection and Reliability Analysis of Structures in Cold Regions"	Urabe, N. Yoshitake, A.	POAC '81	1982	302
"A Review of Icebreaking Technology"	Vance, George P.	M.I.T. - Arctic Technology & Policy	1983	303
"Characterization of Offshore & Coastal Ice Conditions"	Vaudrey, Kennan D.	ASCE - Design for Ice Forces	1983	304
"Design of Prefabricated Offshore Structures for Ice Forces"	Watt, Brian J.	ASCE - Design for Ice Forces	1983	305
"Probability Distributions for Structural Loading By Multiyear Ice Floes"	Wheeler, J.D.	POAC '81	1982	306

LIST OF TECHNICAL PUBLICATIONS

DESIGN GUIDELINES

Title	Author	Publication	Publication Date	Page No.
Ice Engineering Design of Marine Piling and Piers	Wortley, C. A.	Proc. ASCE, J. Tech. Councils, 108(1982)TC2, Nov. Paper no. 17491	1982	307

SOURCE

Aleinikov, S. M.; Lyapin, B. E., Zhidkikh, M. I. (et al)
"Protection of Hydraulic Structures from Icing"
In: Proc. IAHR Int. Symp. on Ice, Quebec, July 27-31,
1981, Quebec, Univ. Laval, 1981, Vol. II

SUMMARY

The icing of hydraulic structures looked upon as a surface process resulting from collision of water drops with the structure surface followed by their spreading and freezing in the form of ice knots. Both active and passive de-icing techniques are described. The ice adhesion to the structure materials and the effect of various factors on its strength are discussed. On the basis of laboratory, field and theoretical investigations an integrated system designed to facilitate the operation of gates in extended navigation conditions has been developed.

KEY WORD	CLASSIFICATION
Design Guidelines	Ice Forces

SOURCE

Bercha, F. G.; Danys, J. V.; Rokne, J. G.
"Probabilistic Ice-Structure Interaction Theory"
In: Proc. IAHR Symp. on Ice Problems, Luleaa (Sweden), Aug. 1978, Luleaa, Int. Assoc. Hydraul. Res., Section for Ice Problems, 1978, Part I, Ice Forces on Structures

SUMMARY

The development of a theory for selecting design ice forces for conical and cylindrical bottom-founded offshore structures was carried out utilizing probabilistic analytical methods and associated computational techniques. Flexural and crushing ice sheet failure phenomena were described utilizing extensions of the customary deterministic theories. Methods of probablistic analysis, involving random variable techniques, were utilized to generate a set of probabilistic equations describing each of the pure mode interactions.

KEYWORD	CLASSIFICATION
Design Guidelines	Ice Forces

SOURCE

Boaz, I. B.; Bhula, D. N.
"A Steel Production Structure for the Alaskan Beaufort Sea"
Thirteenth Annual Offshore Technology Conference 1981:
proceedings - Dallas: Offshore Technology Conference,
1981, V. 3
OTC Paper 4113

SUMMARY

This paper describes the preliminary design of a steel production structure for use in the Alaskan Beaufort Sea. The Controlled Stiffness Steel Arctic Cone (COSSAC) is designed as an enclosed and fully integrated system. To minimize offshore hook-up time and costs, the entire structure is constructed and fully outfitted with production facilities in a graving dock and towed to its installation site. The structural design is based on the use of controlling relative stiffnesses of the primary structural members to distribute the concentrated load effects from multi-year ice features. This concept also results in lower temperature stresses than for a fully restrained system. The design has included the evaluation of forces and stresses due to ice, wind, waves, temperature changes, thaw subsidence as well as construction, transportation and installation of effects.

KEY WORD	CLASSIFICATION
Design Guidelines	Environmental loads

SOURCE

Brunn, Professor,; Geir Moe, Associated Professor
Norwegian Institute of Technology, Trondheim, Norway
"Design Criteria for Nearshore and Offshore Structures Under Arctic Conditions"
POAC'81 - Proceedings of Port and Ocean Engineering Under Arctic Conditions 1981

SUMMARY

A review of the probability based reliability analyses for design of offshore structures is given. Reliability analyses with varying degree of sophistication are discussed, concentrating on the simplest method, the so-called Level I method, which utilizes so-called characteristic values and partial safety factors. Problems with this method is discussed. Then a state of the art review is given on design of coastal and harbour structures in the arctic. Finally the coastal engineering practices are discussed in light of the above mentioned reliability analysis method, Level I.

KEY WORD	CLASSIFICATION
Design Guidelines	Selection of Alternatives

SOURCE

Cammaert, A.B., Manager, Engineering Studies, Acres-Santa Fe Incorporated
Calgary, Canada; Tzinker, G.P., Lead Engineer. Acres Consulting Services
Ltd., Niagara Falls, Canada
"Impact of Large Ice Floes and Icebergs on Marine Structures"
POAC'81 - Proceedings of Port and Ocean Engineering under
Arctic Conditions. 1981

SUMMARY

In recent engineering studies it has been necessary to calculate the impact of large ice features on various types of marine structures. A simple approach was developed which relates kinetic energy dissipation to progressive crushing of the ice. When a large ice floe or iceberg collides with a massive structure the contact zone will fail by crushing, and will increase in size as the resisting force is steadily increased. The kinetic energy is then decreased until an equilibrium point is reached. An analysis of an ice flow impact on a sluice gate will first be presented to illustrate the methods. The particular case of a "blocky" iceberg colliding with either a cylindrical or a conical gravity platform will then be analyzed. For typical iceberg characteristics and structure dimensions, it will be demonstrated that a gravity structure could be designed to withstand iceberg loadings. The effect of structure movements will also be considered.

KEY WORD	CLASSIFICATION
Detail Design	Gravity Structures

SOURCE

Czerniak, Martin T., P.E., Associated Director, Tetra Tech. Inc. Pasadena, Calif.; Arthur T. Shak, P.E., Senior Engineer; J. Ian Collins, Ph.D.,P.E., Vice President
"Design Factors for Rubble Mound Structures Under Ice and Wave Attack" POAC'81 - Proceedings of Port and Ocean Engineering under Arctic Conditions. 1981

SUMMARY

This paper presents an overview of the factors affecting the design of rubble mound and slope protection structures in ice-infested waters. Discussions center on long service life structures in exposed waters where wave and ice conditions impacting the structure are severe. Specific concerns of ice-structure interaction are discussed with reference to some cases found in nature and on manmade structures. A design-development approach is outlined which is being used to determine appropriate combinations of slope geometry and slope protection for various imposed design conditions.

KEY WORD	CLASSIFICATION
Detail Design	Breakwaters & Causeways

SOURCE

Czerniak, M. T.; Collins, J. I.; Shak, A. T.
"Slope Protection for Artificial Island"
Ocean Industry, 16(1981)8, Aug.

SUMMARY

A research project entitled "Slope Protection Design Developed for Beaufort Sea Islands" is presented. The article describes the weather conditions in this area both in ice-free season and ice season, construction constraints and slope protection considerations. The project includes wave and ice model tests.

KEY WORD	CLASSIFICATION
Design Guidelines	Causeway or Breakwater Structures

SOURCE

Jacques L. Dery, President, Jacques Dery & Ass. Inc. Groupe Lavalin, Canada
"Design of Wharves for Winter Navigation in the St. Lawrence River"
POAC'81 - Proceedings of Port and Ocean Engineering Under Arctic Conditions

SUMMARY

Although there are records of winter nagivation on the St. Lawrence river going back a great number of years, navigation in ice-bound waters throughout the winter season from Montreal to the ocean has been on a regular schedule for the last twenty years only. In this paper, ice and climate conditions prevailing in the St. Lawrence valley during the winter season is established, and a short history of wharf design in the area is presented. Ice problems encountered in wharf design are identified and solutions are given.

KEY WORD	CLASSIFICATION
Design Guidelines	Environmental Loads

SOURCE

Enkvist, E.; Varsta, P.; Riska, K.
"The Ship Ice Interaction"
In: POAC 79, 5th Int. Conf. Port and Ocean Eng.
under Arctic Conditions, Norw. Inst. Technol.,
1979, Trondheim, Univ. Trondheim, 1979, Procs. Vol. II

SUMMARY

The loading conditions for hull structure design are reviewed. Aspects of ice parameters, failure criteria, ice pressure and total ice load are described. Semi-analytical ice load models are mentioned. Full-scale measurements are discussed and some results presented. Long-term measurements during normal ship operation have proved useful, and results also from such tests with an icebreaker are presented.

KEY WORD	CLASSIFICATION
Design Guidelines	Functional Planning

SOURCE

Gaythwaite, J. W.
"Structural Design Consideration in the Marine Environment"
J. Boston Soc. Civ. Eng. Sect. ASCE, 65(1978)3

SUMMARY

Various factors peculiar to the marine environment, affecting structural design, have been discussed. All of these factors should be considered for their potential effect, although they ultimately may not affect a given structure. The ocean environment is one in which environmental loadings must be more carefully investigated than on land-based structures and is an environment in which materials generally deteriorate much more quickly, wind, waves, currents, ice, hydrostatic pressure, and impact are the primary sources of loadings a structure must contend with, while it must also stand up to deteriorating agents such as corrosion, attack by marine organisms, wear and fatigue.

KEY WORD	CLASSIFICATION
Design Guidelines	Environmental Loads

SOURCE

Gerard, Robert
"River and Lake Ice Processes Relevant to Ice Loads"
American Society of Civil Engineers - Design for Ice Forces. 1983

SUMMARY

Ice processes that influence conditions for assessing ice loads on structures in rivers and lakes are briefly reviewed. The intent is to provide an appreciation of the range of ice behavior that can occur and to indicate those conditions for which engineering estimates are possible and those which remain qualitative.

KEY WORD	CLASSIFICATION
Design Guidelines	Environmental Loads

SOURCE

Gerwick, Jr. Ben C., Professor of Civil Engineering, University of
  California, Berkeley
"Concrete Structures for the Arctic"
Arctic Technology & Policy - Proceedings of the Second Annual M.I.T. Sea
Grant College Program Lecture and Seminar

SUMMARY

Responding to the current intense interest in the exploration for and development of petroleum resources in offshore Arctic and sub-Arctic areas, considerable design and development efforts have recently been directed to prestressed concrete caissons. The successful use of concrete offshore platforms in the North Sea and concrete lighthouses in the Baltic Sea and Eastern Canada have encouraged consideration of concrete for structures in the extremely hostile environment of the Arctic where ice is a dominant design force.

Prestressed and reinforced concrete exhibits ductile behavior under impact at low temperaturees. Properly designed and constructed, it is highly durable under the multiple attack phenomena of saline water, freeze-thaw cycling, ice abrasion, and thermal strains.

Thick shell or slab elements are typically employed as the peripheral ice wall. With substantial quantities of reinforcing and prestressing steel, including through wall stirrups, high resistance to local concentrated loads ("punching shear") and a ductile behavior under overload can be attained.

While early attention has focussed primarily on the configuration of the ice wall, the internal structural configuration must be designed to distribute and transfer the intense loads to the base and into the foundation soils. Concrete shear walls, diaphragms, and biaxially-prestressed slabs are structurally effective for this purpose.

Structural lightweight concrete can be employed to reduce the draft of structures in the shallow waters of the Beaufort Sea and has been successfully used on the caissons for the Tarsiut island in Canada.

Some areas for future development are indicated, including use of silica fumes to increase strength, steel-concrete composite sandwich construction, utilization of multiaxial stress conditions, and coatings to reduce friction and abrasion.

KEY WORD	CLASSIFICATION
Detail Design	Gravity Structures Material Selection

SOURCE

Haynes, F. Donald
"Survey of Design Criteria for Harbors and Channels in Cold Regions" (an
Annotated Bibliography)
Cold Regions Research and Engineering Lab Hanover N.H.
Corp. Source Codes: 038100
Sponsor: Office of the Chief of Engineers (Army)
Washington, D.C. Civil Works Directorate
Report No: CRREL-76-3
Mar 76

SUMMARY

A world-wide review of the literature applicable to the design of harbors and channels in cold regions was conducted. Forces due to ice movement present the dominant factor in the design of marine structures in cold regions. Expressions for calculating the ice force are presented. Other factors relating to design criteria such as construction materials, structure geometry, and methods of ice suppression are discussed.

KEY WORD	CLASSIFICATION
Design Guidelines	Selection of Alternatives Ice Aspects in Design Codes & Guidelines

SOURCE

Holand, Ivar, professor; Moan, Torgeir, professor, The Norweigian Institute
of Techology, Norway
"Risk Assessment of Offshore Structures Experience and Principles"
POAC's - Proceedings of Port and Ocean Engineering Under Arctic Conditions.
1981

SUMMARY

A risk assessment of offshore structures in northern waters is essential because of the particularly severe environmental conditions and the size of the installations.

Statistics of fatal accidents in Norweigian oil activities are summarized and show that structural failures in floating structures and helicopters dominate.

Statistics for structure-induced accidents in world-wide operation are presented with reference to a compilation from Lloyds' list by Det norske Veritas. An important conclusion is that the accident rate for mobile platforms is much greater than for fixed platforms.

Systematic risk analyses are necessary as a basis for a reliable risk assessment. Methods of risk analyses and the application of the results are outlined.

In the design against catastrophes, the notions of accidental loads and barriers are essential.

Finally, safety management and the role of government control are discussed, and some conclusions concerning safety and economy are quoted.

KEY WORD	CLASSIFICATION
Design Guidelines	Environmental Loads Conceptual Design

SOURCE

Jordaan, Ian J.; Det norske Veritas (Canada) Ltd. Calgary, Alberta, Canada
"Risk and Safety Assessment for Arctic Offshore Projects"
Arctic Technology and Policy - Proceedings of the Second Annual M.I.T. Sea
Grant College Program Lecture and Seminar. 1983

SUMMARY

Risk is defined in terms of both the probability, generally small, and the undesirabiity of an event. Risk analysis is a systematic procedure requiring estimation of probabilities and an analysis of the consequences of the event. It can be seen as part of the decision-making procedure and is aimed at determining an optimal decision from a set of possible actions, in addition to delineating levels of risk. The methodology is most suitable for problems in frontier areas of technology such as are involved in Arctic projects. Some typical problems are discussed in a general way, such as the choice between fixed and mobile production systems in iceberg-infested waters. Environmental loading and the probabilistic analysis of pressure ridges as a Poisson process are discussed. An example of application to the risk of scour of a pipeline system is given. The use of utility theory for combining attributes is suggested as a fruitful area for further development. Practical guides for dealing with problems of risk are discussed.

KEY WORD	CLASSIFICATION
Design Guidelines	Environmental Loads Conceptual Design - Information Deficiencies and Recommended Research and Development

SOURCE

Kivisild, Hans R., Vice-President, Fenco Engineers Inc., Canada
"Marine Foundations"
POAC'81

SUMMARY

Present-day experience is that jacket foundations are most economical for open ocean and conditions. There has been a definite shift to jacket structures in the North Sea and offshore structures elsewhere are continuing to be jacket structures. These trends apply in Canada offshore areas at Sable Island and Queen Charlotte Islands.

Piled foundations have been widely used for drilling and production platforms, resisting open water shear and overturning forces. Forces acting on these structures are an order of magnitude less than arctic ice forces. Therefore, in all Canadian areas, except Sable Island and the Queen Charlote Islands, extensive massive piling is required. Gravity-type structures made of concrete or steel are suitable for high thrust situations.

In arctic waters, earth mounds, confined earth islands and confined gravel islands have been used or are being installed. Essentially, these structures transmit ice forces to foundations by gravity.

For deeper water, structures with gravity foundations have been proposed for Candian waters. The result is a heavier structure designed for different conditions than the ocean structures described above.

Wherever proper soil conditions are available, gravity structures can be placed directly on the bed, or, in greater water depth, on earth or rockfill mounds. Subbases have been shown to be able to withstand the erosion and ice forces. Oceanbed protection has been achieved by rock fills, mattresses or baffeling elements.

Floating mooring facilities and floating platforms are also indicated in ice-covered areas. In ice-affected areas, this type of structure would need a special anchor system to be developed since forces on the anchor system could be expected to be larger than anchor forces in open water conditions. New developments in anchor design are also necessary if more rigid floating structures such as tension-leg platforms and guyed tower structures are to be used in Canadian offshore waters.

KEY WORD	CLASSIFICATION
Design Design	Gravity Structures
	Structure Systems
	Floating Structures

SOURCE

Lewis, A.E.; Bechtel, Inc., Houston, TX. Pipeline Div.
"Arctic Terminal for Icebreaking Tankers Study; Conceptual Design"
Maritime Administration, Washington, DC. Office of Port and Intermodal
Development
Report No: JOB-12963; 1MA-RD-970-79049
Mar. 79

SUMMARY

This report represents the conceptual design for a marine terminal located at Wainwright, on the northwest coast of Alaska, to transfer crude oil to 250,000 dwt icebreaking, or ice strengthened tankers on a year around basis. The purpose was to determine the approximate cost of such a terminal as a preliminary guide for use in long range planning by Federal and State agencies, as well as by commercial firms having interests in the area. The site is situated to serve potential oil fields in northwest Alaska, the National Petroleum Reserve in Alaska, or offshore wells under the relatively near shore part of the Chukchi Sea. The initial throughput capacity is 500,000 barrels per day with phased expansion up to 2,000,000 bpd. The terminal in the first phase consists of a single offshore mooring tower in 120 feet of water about 5 miles offshore connected by buried pipeline to an on shore facility with 5.2 million barrel storage capacity for oil. The final phase consists of three offshore towers and a total of 10.4 million barrel oil storage capacity. The contractor was assisted by an Advisory Group of interested oil company and shipping company representatives.

KEY WORD	CLASSIFICATION
Design Guidelines	Functional Planning Conceptual Design

SOURCE

Maattanen, Mauri
"Design of Navigational Structures for Ice Forces"
American Society of Civil Engineers - Design for Ice Forces. 1983

SUMMARY

An overview of ice conditions and the types of ice action that are hazardous to navigational stuctures is presented. Depending on the circumstances, ice failure against structures occurs by crushing, bending, splitting, or plastic yielding. Methods for predicting ice forces against typical navigational structures are presented. These structures include offshore structures, such as lighthouses and piers, and landfast structures, such as breakwaters, locks, and dams. Both static and dynamic ice forces, particularly dynamic ice-structure interactions involving slender, bottom-founded structures, are described. Design recommendations and ways to avoid or minimize adverse ice effects are presented and discussed.

KEY WORD	CLASSIFICATION
Design Guidelines	Environmental Loads Conceptual Design

SOURCE

Machemehl, Jerry L., M. ASCE
"Design of Manmade Offshore Islands for Ice Forces"
American Society of Civil Engineers - Design for Ice Forces. 1983

SUMMARY

Approximately sixty percent of the undiscovered oil and fifty percent of the undiscovered gas probably lies in the sedimentary basins offshore Alaska (USGS 1980) Because of this hydrocarbon potential, both domestic and international oil companies have been actively exploring for oil and gas in the offshore regions of the Arctic since the early 1970's. As part of this exploration effort, the oil companies have been constructing fill islands capable of resisting both global and local ice movements since 1973.

KEY WORD	CLASSIFICATION
Detail Design	Gravity Structures

SOURCE

Maxwell, S.V., McGonigal, D., and Graham, C., Gulf Canada Resources Inc.
Calgary, Canada
"Artifical Islands and Steel Structures in the Beaufort Sea"
Arctic Technology and Policy - Proceedings of the Second Annual M.I.T. Sea Grant College Program Lecture and Seminar.

SUMMARY

This paper presents a brief history of the evolution of artificial islands and caisson structures for oil exploration in the Beaufort Sea. Following a brief summary of the oceanographic environment and seafloor geology of the Beaufort, the factors influencing design and construction of structures are discussed with examples from oil industry experience in the north. Next, several case histories of islands and caissons are described. The current planning philosophy for the building of production platforms is also discussed, and finally the areas where new developments are needed are outlined.

KEY WORD	CLASSIFICATION
Design Guidelines	Gravity Structures Material Selection Concrete

SOURCE

Michel, Bernard
"Cold Regions Science and Engineering Monograph 3, Section 81b: Ice Pressure
on Engineering Structures"
Cold Regions Research and Engineering Lab Hanover N H
Corp. Source Codes: 037100
Report No.: CRREL-CRSE-3-BLB
Jun 70

SUMMARY

The monograph summarizes existing knowledge on forces exerted by an expanding ice sheet, impact forces of ice on structures, and vertical forces exerted by ice on hydraulic structures. Sections are also devoted to icebreakers and ice models.

KEY WORD	CLASSIFICATION
Design Guidelines	Environmental loads

SOURCE

Nakawo, M.
"Heat Exchange at Surface of Built-Up Ice Platform During Construction"
Cold Regions Science and Technology, V. 3, No. 4, Aug. 1980

SUMMARY

Heat budget observations show that sensible heat loss accounts for most of the latent heat released during freezing of an exposed, shallow-water layer in the high Arctic in January. Combined evaporation and sensible heat losses were about four times larger for this flooding situation than expected in neutral conditions. Empirical and semi-empirical equations are derived for estimating the components of the heat flux from meteorological parameters.

KEY WORD	CLASSIFICATION
Design Guidelines	Environmental Loads

SOURCE

Neill, Charles R., M. ASCE
"Design of Bridges for Ice Forces"
American Society of Civil·Engineers - Design for Ice Forces. 1983

SUMMARY

Sources of knowledge on ice forces and ice effects on bridges are listed and discussed briefly. Comments are made on experience of damage by ice and on the influence on bridge costs of design for ice. North American and USSR code requirements are outlined, and relevant ice conditions in rivers and lakes are discussed. Methods of estimating ice forces are given for various modes of ice action, taking into account substructure geometry and other factors. A summary of recommendations is given regarding design of bridges for ice forces.

KEY WORD	CLASSIFICATION
Design Guidelines	Environmental Loads

SOURCE

Neill, Ch. R.
"Dynamic Ice Forces on Piers and Piles, an Assessment of Design
Guidelines in the Light of Recent Research"
Can. J. Civil Eng., 3(1976)2

SUMMARY

The first part of the paper reviews and assesses various analytical approaches and design formulas used to estimate forces due to the impact of moving ice on piles, piers and towers. The application of dimensional analysis to the problem is outlined briefly. The second part reviews and assesses fullscale data available from research and from reported evaluations of structure performance, and attempts to summarize their more significant findings. The third part reviews a number of recent small-scale laboratory investigations. Finally, suggestions are made for improvement of current design guidelines and practices.

KEY WORD	CLASSIFICATION
Design Guidelines	Piled Structures

SOURCE

Noble, Peter G.
"Design of Submerged and Floating Structures"
American Society of Civil Engineers - Design for Ice Forces. 1983

SUMMARY

The objective of this paper is to present an overview of the state-of-the art of ice engineering as applied to submerged and floating structures. In order to accomplish this objective, five specific design studies are reviewed, dealing with aspects of the problem including a water intake pipeline in Great Slave Lake, Northwest Territories (N.W.T.), Canada, an electrical cable crossing in the Great Lakes, a floating ice boom, a floating plant barge for Canadian Arctic operations, and a ship design for a temperate ice regime.

KEY WORD	CLASSIFICATION
Design Guidelines	Environmental Loads

SOURCE

Nottingham, Dennis, M. ASCE, and Drage, Brent T.
"Design of Port and Coastal Structures for Ice Forces"
American Society of Civil Engineers - Design for Ice Forces. 1983

SUMMARY

Design of ice-affected port and coastal structures cannot be addressed in a few single specific terms, but must instead account for a matrix of elements differing at each site. Evaluation of ice forces on port and coastal structures is an integral part of design in relationship with tides, currents, coastal processes and freezing index, among other factors. These interrelationships are discussed and quantified in relation to design applications using the best information now available. Various concepts and types of structures with potential for use in ice environments are presented.

KEY WORD	CLASSIFICATION
Design Guidelines	Environmental Loads Conceptual Design

SOURCE

Prodanovic, Anton, Senior Research Specialist
"Upper Bounds of Ridge Pressure on Structures"
Exxon Production Research Co. Houston, Texas, USA
POAC 1981

SUMMARY

Arctic offshore structures must be designed to withstand moving ice ridges, either unconsolidated or consolidated. The ridges are most likely to fail in crushing, shearing, or in-plane bending against cylindrical and vertical flat-sided structures. The ridge failure pattern may include out-of-plane bending against conical and inclined flat-sided structures.

In this paper, several ridge failure patterns are reviewed and plasticity theory is used to calculate upper bounds of pressures resulting from ridge crushing and shearing. The Mohr-Coulomb failure criterion, considered applicable for unconsolidated ridges, and a quadratic failure criterion, considered appliable for consolidated ridges, are used in the analysis. The upper bounds are presented in a dimensionless form for typical ridge cross-section shapes, as functions of normalized ice strengths and ridge and structure dimensions.

KEY WORD	CLASSIFICATION
Design Guidelines	Environmental loads Conceptual Design

SOURCE

Public Works Canada, Western Region
"General Cargo Marine Terminal Frobisher Bay, NWT. -
Preliminary Engineering Report"
July 1980

SUMMARY

The preliminary engineering report prepared by Public Works Canada is for a marine terminal facility at Innuit Head, Frobisher Bay NWT. The completed facility would consist of a deep sea wharf, an open storage area, a transit shed and an access roadway.

The report examines a number of engineering solutions for a wharf, their evaluations and recommends a solution, in detail. The report also evaluates various implementation options, their practicality, duration, cost implication and outlines method of construction.

Informative appendices includes, geotechnical investigations, wind data, hindcast wave data and seawater temperature and salinity at the proposed site.

KEY WORD	CLASSIFICATION
Design Guidelines	Conceptual Design Construction Planning and Scheduling

SOURCE

Ralston, T. D.
"Ice Force Design Considerations for Conical Offshore Structrures"
In: POAC 77, 4th Int. Conf. Port and Ocean Eng. under Arctic Cond., Mem. Univ. Newfoundland, St. Johns, Sept. 26-30, 1977, St. Johns, Ocean Eng. Inf. Centre, 1978, Vol. 2

SUMMARY

Analytical and model basin studies of sheet ice failure against conical structures have been previously discussed in the literature. The analytical work was based on a linear elastic description of ice deformation, with a brittle failure criterion, and was found to underestimate the model basin data. A new analysis has been developed that considers a floating ice sheet to be an elastic-plastic plate resting on an elastic-plastic foundation. The upper bound procedure of plastic limit analysis leads to a mathematical model for both sheet ice failure and rideup on a conical structure.

KEY WORD	CLASSIFICATION
Design Guidelines	Gravity Structures - Cone Shaped

SOURCE

Robbins, R. J.; Verity, P. H.; Taylor, T. P.; Metge, M.
"Techniques for The Study of Ice, Structure Interaction"
In: Proc. Third Int. Conf. on Port and Ocean Eng.
under Arctic Conditions, Fairbanks, Univ. Alaska, Inst.
Mar. SCI., 11-15 Aug. 1975, Fairbanks, Univ. Alaska, 1976
Vol. II, Section 9 - Structures

SUMMARY

Design conditions for two classes of Arctic offshore drilling platforms have been investigated with unique experimental techniques. A facility was designed and built to permit the evaluation of the interaction between a conical bottom founded drilling platform and moving ice sheets. A small prototype structure is positioned in large ice test basin with a built-in towing system which moves naturally grown ice sheets past the prototype structure. The design and operation of the basin is described and a typical qualitative result of an ice/cone interaction is presented.

KEY WORK	CLASSIFICATION
Design Guidelines	Floating Structures

SOURCE

Rojansky, M., Gerwick, B.C.
"Failure Modes and Forces of Pressure Ridges acting on Cylindrical Towers"
University of California, Berkeley USA
POAC 1981

SUMMARY

This study is directed at the potential failure modes and sequences of failure of a typical sea ice pressure ridge impinging against the vertical cylindrical shaft of an offshore gravity platform. From these analyses, the maximum forces acting on the structure can be bounded.

It was found that in the case of short ridges, the sheet behind the ridge will fail in crushing and create a rubble field. For longer ridges, the failure will be due to flexure. The critical length is a function of the geometry and kinematics of each given situation.

Since actual pressure ridges will often have both consolidated and unconsolidated zones, a transformed section has been adopted.

The indentation problem is addressed analytically, and the indentation factor is shown to vary non-linearly with the aspect ratio, being comparable to previously published empirical data for both large and small aspect ratios but lying below them for intermediate ratios.

A ridge which is incorporated within an isolated ice floe may exert a significant impact force when it impinges on a structure. The analysis for impact considers a series of increments for each of which the variations in apparent crushing strength due to changing strain rates and aspect ratios are considered.

A numerical example is presented in order to demonstrate the principle that the "minimum required energy to failure concept" should be adopted in order to determine the mode or modes of failure and the maximum forces imposed on the structure.

KEY WORD	CLASSIFICATION
Design Guidelines	Environmental loads

SOURCE

Saunders, T.F., Timascheff, M.,
"Ice Effects on Planning, Design and Operation of A Major Oil Terminal"
Proceedings of 23rd International Navigation Congress, Ottawa, 1973.

SUMMARY

This paper presents a review of planning, design and operation of a major marine terminal at St. Romauld on the St. Lawrence River, Québec for Golden Eagle Canada Limited. The site is a particularly difficult one, considering severe ice and tidal current conditions. It is a good example of close co-operation between designers, constructors and operators in producing a year round operational facility. A particularly interesting feature, is the utilization of stationary ice breaker cells to protect the berthing area from large ice flows.

KEY WORD	CLASSIFICATION
Design Guidelines	Functional Planning Design Principles Construction Techniques

SOURCE

Saunders, T.F., Sr. Vice President, Fenco Engineers Inc., Toronto
"Cold Region Canadian Port Development"
3rd International Ocean Development Conference
Tokyo, Japan 1975

SUMMARY

In Canada, the search for, and development of mineral resources in the Northern sections of the country is accelerating. These are vast unpopulated areas, remote from supply centres with harsh environmental conditions. The land yields its wealth grudgingly and only after substantial effort by man.

This paper presents the development of the most northerly Asbestos Mine in Canada. In particular, it describes the port facilities, at Deception Bay, which were provided to ship out the mine product and bring in the essential fuel and supplies within the annual three month ice-free shipping period.

The work at Deception Bay consisted of storage facilities for 230,000 tons of coarse asbestos fibre, wharf facilities to accommodate ore carriers of up to 50,000 DWT capacity and all the mechanical systems required to store, reclaim and load the fibre aboard the vessels. In addition, fuel storage, power house and truck dumping stations are located at this site.

KEY WORD	CLASSIFICATION
Design Principles	Design Methodology Gravity Structurs Transportation and Logistics

SOURCE

Sinclair, D. A.
"SNIP-II-57-75 Construction Standards and Rules, Part II Design
Standards, Chapter 57: Loads Exerted on Hydraulic Structures by
Waves, Ice and Ships
Ottawa: National Research Council, 1980

SUMMARY

Canada and the Soviet Union share ... similar problems with ice loads on structures. Soviet experience in dealing with ice problems has resulted in the publication of ice codes in 1959, 1967 and now most recently in 1976. There are now efforts in Canada to revise and update existing ice codes here. It was felt that the translation of this most recent Soviet Code would be a useful contribution to Canadian engineers and code writers. Only the part on ice of a chapter in SNIP II-57-75 ... has been translated and printed in this publication. ...

Key WORD	CLASSIFICATION
Design Guidelines	Environmental loads

SOURCE

Slomski, S.; Vivatrat, V.
"Selection of Design Ice Pressures and Application to
Impact Load Prediction"
In: POAC 83, Proc. 7th Int. Conf. on Port and Ocean Eng,
under Arctic Conditions, Helsinki, April 1983, Espoo, VTT,
1983, Vol. 2

SUMMARY

A probablistic model is proposed to predict the relationship between the cumulative probability functions of the effective ice pressure during impact and the peak identation pressure. The prediction is compared with existing field measurements. A Monte Carlo simulation procedure is used to combine the probabilistic ice pressure selection with the probability of occurrence of floe dimensions and velocity in a computer program for predicting the maximum annual impact load in terms of floe impact frequency. The simulation results also provide a basis for selecting design ice pressure for different loaded area sizes.

KEY WORD	CLASSIFICATION
Design Guidelines	Ice loads

SOURCE

Sodhi, D.S., Haynes, F.D.
"Measurement of Ice Forces on Structures"
American Society of Civil Engineers - Design for Ice Forces. 1983

SUMMARY

Methodologies and techniques are discussed for measuring ice forces on fixed structures situated in rivers and lakes. The usual method of measuring ice forces is to place a load frame between the moving ice and the structure and to measure the reactive forces and load cells or strain gages. Another method is to measure the accelertion, displacement or strain at a few points on the test structure and relate the measurements to ice forces. The size and shape of the force measuring system depend upon the mode of ice failure, the distribution of the ice forces and the logistics associated with each site. The variations of ice force with respect to time are generally very high during crushing and impact, and the response of the force-measuring system should be sufficiently fast.

The presentation of data from past efforts to measure ice forces has been in the form of peak force levels, plots of ice force with respect to time, and frequency spectra.

KEY WORD	CLASSIFICATION
Design Guidelines	Environmental Loads

SOURCE

Timmermans, W.J.
"Design of Offshire Pipelines for Ice Environments" Member ASCE
American Society of Civil Engineers - Design for Ice Forces. 1983

SUMMARY

Design and installation of offshore pipelines in cold regions requires special care. Low ambient temperatures may cause increased friction losses in oil and gas lines due to wax crystallization or hydrate formation. Environmental conditions in these areas are described. Installation methods in cold regions are different from those normally used, to take into account presence of surface ice during most of the year. Protection of pipe against bottom gouging ice masses is essential; several methods are outlined.

KEY WORD	CLASSIFICATION
Design Guidelines	Environmental Loads

SOURCE

Urabe, N., Toshitake, A.
"Steel Selection System and Reliability Analysis of Structures in Cold Regions"
Technical Research Center, Hawasaki-city, Kanagawa; Nippon Kokan K.K. Japan
POAC 1981

SUMMARY

To make sure a safety performance of ice breakers or structures in cold regions, usual deterministic way to select steels is no longer appliable, since environmental conditions such as ice-structure interation forces, and temperature, and even mechanical properties of steels show considerable scatter. Therefore, those variables must be considered as statistical manners.

In this paper we describe a method based on reliability analysis to select steels which should be used for the ice breakers and structures in the cold sea area. The method was also applied to analyse the safety assessment of the structures and to design a structure possessing both of fail security and economy.

Distribution functions of fracture toughness value of steels and imperfections inherently existing in the structures were surveyed by means of fracture toughness tests and non-destructive investigations, respectively. Uncertainties involved in each processes were cleared through probabilistic manipulations.

Finally, the probability of failure was quantified for the structures under given conditions. Imperfections which have not been detected by the NDI grow under fluctuation of the stresses, then the probability of the failure increased when service period was prolonged.

Reliability level for steel selection and for structure designing criterion was, then, determined by reflecting on the economy due to non-destructive invetigation details, inspection interval and so on.

KEY WORD	CLASSIFICATION
Design Guidelines	Steel Structures

SOURCE

Vance, George P.
"A Review of Icebreaking Technology"
Mobil Research and Development Corporation
Offshore Engineering Farmers Branch, Texas 75234

SUMMARY

This paper traces the history of icebreaking technology from its early stages of educated guesses by ship designers to the sophisticated computer techniques utilized by current day Naval Architects and Structural Engineers. The paper covers the broad spectrum from the analytical techniques utilized to predict ship resistance to the methods used to predict the forces on offshore steel and concrete structures and gravel islands.

KEY WORD	CLASSIFICATION
Design Guidelines	Steel Structures Concrete Structures

SOURCE

Vaudrey, Kennon D., M. ASCE
"Characterization of Offshore and Coastal Ice Conditions"
American Society of Civil Engineers - Design for Ice Forces. 1983

SUMMARY

Seasonal sea ice conditions typical of nearshore coastal zones are reviewed. Prominent ice features influencing design ice conditions for offshore structures are described. This chapter is intended to provide an appreciation for sea ice behavior and its dependency on meteorological and oceanographic conditions.

KEY WORD	**CLASSIFICATION**
Design Guidelines	Environmental loads

SOURCE

Watt, Brian J., M. ASCE
"Design of Prefabricated Offshore Structures for Ice Forces"
American Society of Civil Engineers - Design for Ice Forces. 1983

SUMMARY

The design of fixed offshore structures to resist forces from sea ice features is reviewed. Methods for predicting global ice loads on towers, wide indenters and cones are considered, together with expected trends in force prediction methodology. The question of developing appropriate local ice pressure criteria is addressed. Key design issues are identified for several structure types including steel and concrete towers, caisson islands and cone structures. Finally particular design concerns are identified for arctic application of steel and concrete structures.

KEY WORD	CLASSIFICATION
Design Guidelines	Ice loads

SOURCE

Wheeler, J.D., Research Advisor
"Probability Distributions for Structure Loading by Multiyear Ice Floes"
Exxon Production Research Company, Houston, Texas
POAC'81

SUMMARY

Possible encounter with multiyear ice floes must be allowed for in the design of bottom-founded offshore structures in the arctic. Given a knowledge of sea-ice mechanics and of the failure mode imposed by structure geometry on a multiyear floe, there will be uncertainty as to the diameter, thickness and number of such floes that may impact a structure in different seasons of the year. This paper describes procedures for calculating probability distributions for multiyear ice loads on a structure during open-pack conditions (e.g., breakup, summer invasions, seasonal pack) and consolidated-pack conditions (winter). Information on floe diameters and thickness, a real ice coverge, ice movement and ice strength are combined in a Monte Carlo calculation to develop the probability of exceedance (risk) versus loading in each season. Variation of ice thickness through the year and variation in point of contact between structure and floe are allowed for. Sensitivity of results to several types of environmental data is examined using reasonable but fictitious values for environmental parameters.

KEY WORD	CLASSIFICATION
Conceptual Design	Environmental loads

SOURCE

Wortley, C. A.
"Ice Engineering Design of Marine Piling and Piers"
Proc. ASCE, J. Tech. Councils, 108(1982)TC2, Nov. Paper
no. 17491

SUMMARY

Design criteria and structure designs for pilings, piers, and docks subject to ice are presented. Included are estimates of stationary and moving horizontal and vertical ice forces, types of constructions and materials, facility layouts to mitigate ice problems, and methods of ice suppression. Design recommendations are based on actual design experiences, field investigations in several hundred U.S. and Canadian Great Lakes harbors and ports over a period of years, and laboratory studies.

KEY WORD	CLASSIFICATION
Design Guidelines	Piled Structures

6.0 CONSTRUCTION PROCEDURES AND TECHNIQUES

LIST OF TECHNICAL PUBLICATIONS

CONSTRUCTION PROCEDURES AND TECHNIQUES

Title	Author	Publication	Publication Date	Page No.
"Nansen Drift Station Project - Remote Sea-Ice Runway Construction"	Barthelemy, J.L.	Civil Engineering Lab (Navy), Port Hueneme, California Report No. CEL-TN-865	1978	308
The Construction of an Artificial Drilling Island in Intermediate Water Depths in the Beaufort Sea	Boone, D. J.	Twelfth Annual Offshore Technology Conference 1980, proceedings Dallas: Offshore Technology Conference 1980, V. 4	1980	309
"Air Inflated Portable Maintenance Shelter"	Brier, F.W.	Civil Engineering Lab (Navy), Port Hueneme, California Report No. CEL-TN-1395	1975	310
Island Construction in the Beaufort Sea	Dingle, P. J.	Esso Resources Canada Limited Edmonton, Alberta	1979	311
"Polar Structures, the NCEL Family of Wanigans"	Dykins, J.E., Sherwood, G.E., Hoffman, C.R.	Civil Engineering Lab (Navy), Port Hueneme, California Report No. NCEL-R309	1975	312
Monopod Drilling Unit for the Beaufort Sea Specifications: Construction and Outfitting	Earl and Wright Consulting Engineers	Imperial Oil Limited Calgary: Distributed by APOA, 1974 APOA Project No. 110: Conical and Cylindrical Gravity Structures for Southern Beaufort Sea. Report No. 7	1974	313
Environmental Evaluation Summary of Construction and Construction Support Activities Related to the Proposed Ten Year Beaufort Sea Offshore Exploration Program	F.F. Slaney & Company	Imperial Oil Limited Vancouver, B.C.	Unpublished Report	314

LIST OF TECHNICAL PUBLICATIONS

CONSTRUCTION PROCEDURES AND TECHNIQUES

Title	Author	Publication	Publication Date	Page No.
"Construction of a Deep-sea Dock in the Arctic"	Girgrah, M. Shah, V.K.	POAC '77	1977	315
"Design Data for the Development of Portable, Infrared Radiant Heaters"	Guzdar, Adi R., Rhee, Sang Soon, Harvey, Andrew C.	Foster-Miller Associates Inc. Waltham, Mass. Report No. QM-6933; USA-NLABS-TR-73-14-GP	1972	316
"Pioneer Polar Structures: Erection of Portable Maintenance Shelter"	Hansen, R.W., Sherwood, G.E.	Civil Engineering Lab (Navy), Port Hueneme, California Report No. NCEL-N587	1964	317
"Ice Construction-Investigation of Accelerated Bottom - Freezing Techniques"	Hoffman, C.R., Culbertson, T.L.	Civil Engineering Lab (Navy), Port Hueneme, California Report No. NCEL-TN-1078	1970	318
"Polar Construction Equipment Portable Floodlighting Unit"	Pierce, N.E., Sherwood, G.E.	Civil Engineering Lab (Navy), Port Hueneme, California Report No. NCEL-TR-348	1964	319
"Strathcona Sound Wharf Repairs"	Shah, V.K.	Public Works, Canada	1982	320
"Polar Structure - Design Concept for a Heavy Equipment Field Repair Shelter"	Sherwood, G.E., Moser Jr., E.H.	Foster-Miller Associates Inc. Waltham, Mass. Report No. NCEL-N614	1964	321
"Inflatable Igloo Shelter for Cold-Weather Operations"	Stachiw, Jerry D., . Hascall, Hudson L.C Sorensen, Marc	Naval Undersea Centre, San Diego, California Report No. NUC-TP-428.	1974	322
"Self-Contained Sanitation Systems for 2-15 Man Polar Facilities"	Valentine, B.W.	Civil Engineering Lab (Navy), Port Hueneme, California Report No. NECL-TR-759	1972	323

SOURCE

Barthelemy, J.L.
"Nansen Drift Station Project - Remote Sea-Ice Runway Construction"
Civil Engineering Lab (Navy) Port Hueneme Calif.
Corp. Source Codes: 391111
Report No: CEL-TR-865
Apr 75

SUMMARY

In the past, surface-flooding activities have been confined to areas near major military logistic centers. As a result, techniques developed for sea-ice runway construction relied extensively upon the use of heavy equipment to clear snow and position large stationary pumping equipment. At remote sites, such as that planned for the proposed Nansen Drift Station, requirements are different. Construction crews will be severely restricted as to their size and number of support equipment available, and they may be required to work concurrently at a number of scattered locations. A field-test program conducted by the Civil Engineering Laboratory at Barow, Alaska, during March 1977 added a new dimension to surface-flooding technology. The exercises demonstrated the feasibility and capability of using small, lightweight pumps to prepare sections of a sea-ice runway. The water-handling equipment included two modified, highly portable, centrifugally driven trash pumps that had undergone preliminary low-temperature testing in the cold-chamber facilities at CEL.

KEY WORD	CLASSIFICATION
Equipment Selection & Utilization	Equipment Selection and Utilization

SOURCE

Boone, D. J.
"The Construction of an Artificial Drilling Island in Intermediate Water Depths in the Beaufort Sea"
Twelfth Annual Offshore Technology Conference 1980, proceedings Dallas: Offshore Technology Conference, 1980, V. 4

SUMMARY

In October of 1979, Esso Resources Canada Limited, a wholly-owned subsidiary of Imperial Oil Limited, completed it's 15th artificial drilling island in the Beaufort Sea, 26 km north of the MacKenzie River Delta in the western Canadian Arctic. Issungnak, as the island is known, is unique in size and construction. ...The success of the project hinged on finding sufficient granular borrow material within the range of the suction dredges and their pipelines. ...An on site mini-computer controlled system ensured the accurate placement of fill to optimize the use of construction time. The system was also used to collect hydrographic survey data and generate fill volumes, contour maps, and slope profiles for use in planning construction and dredging strategies. Details of the island construction are presented in this paper with special attention given to site conditions, design criteria, and construction techniques and control. The techniques used include innovative approaches to surveying, dredging, and the use of floating pipelines in hostile marine conditions.

KEY WORD	CLASSIFICATION
Construction Techniques	Material Selection Equipment Selection & Utilization

SOURCE

Brier, F.W.
"Air Inflated Portable Maintenance Shelter"
Civil Engineering Lab (Navy) Port Hueneme Calif.
  Corp. Source Codes: 391111
  Report No: CEL-TN-1395
  Jul 75

SUMMARY

The need for adequate shelter for maintenance and repair of construction and other types of equipment at polar camps motivated development of a portable maintenance shelter. The shelter is a commercially available pneumatic structure composed of an air inflated frame and a nylon-reinforced polyvinyl chloride cover. The 22- by 22-foot shelter is adequate for the repair and maintenance of equipment as large as a size 6 snow tractor. From the field test at Williams Field Antarctica, it was concluded that if fabrication techniques can be improved the shelter will be suitable for use at temporary camps or other facilities in polar regions. However, additional testing is required to determine its durability and low-temperature limitations.

KEY WORD	CLASSIFICATION
LOGISTICS	Maintenance of Equipment Maintenance of Personnel

SOURCE

Dingle, P. J.
"Island Construction in the Beaufort Sea"
Esso Resources Canada Limited
Edmonton, Alberta

SUMMARY

...This paper focuses on the Canadian Beaufort Sea where potential oil reserves are estimated to be 36 million barrels. The construction of artificial islands is one of the key elements of exploration and development programs in the Beaufort. ...Since 1972, Esso Resources Canada Ltd. has constructed 16 artificial exploration islands in this area. Island design criteria for temporary islands include the ability to resist ice forces and summer wave erosion, island fill and seabed foundation stability, sufficient area to support a drilling rig and related activities. ...future islands will be located in the Western Beaufort, an area where sources of contruction material are scarce. The advantages of dredged islands for exploration provide incentive to modify existing design and construction methods for their continual use. One promising concept is the caisson-retained island which would substantially reduce material requirements. A second key to economical projects lies in an efficient and effective equipment spread. Possible combinations under consideration include trailer suction hopper dredges, stationary suction dredges and self-propelled or conventional bottom dump barges. With continued exploration, commerical production in this frontier area is foreseeable. Further development will be needed in the areas providing permanent production platforms and transporting crude to southern markets. This points to a long term need for dredging in oil exploration and production in this area of the world.

KEY WORD	CLASSIFICATION
Construction Techniques	Dredged Material

SOURCE

Dykins, J.E.; Sherwood, G.E.; Hoffman, C.R.
"Polar Structures, the NCEL Family of Wanigans"
Naval Civil Engineering Lab Port Hueneme Calif.
Corp. Source Codes: 000000
Report No: NCEL-R309
9 Jun 64

SUMMARY

The need for portable shelters for trail operations, transient field camps, and remote construction areas in polar regions led to the develoment and evaluation of a family of wanigans. The basic wanigan in this family is the Standard NCEL Sled Wanigan, which is 8 feet wide and 20 feet long. A 10-foot-wide version of this wanigan is called the ExtraWide NCEL Sled Wanigan. Both of thse wanigans must be mounted on bobsleds for mobility. For limited mobility independent of a sled, a heavy-duty floor and skid system was developed for the wanigans. These skid-mounted units are called the Standard NCEL Portable Camp Wanigan and the Extra-Wide NCEL Portable Camp Wanigan. All are of a prefabricated, panelized construction with interchangeable components. The two standard wanigans are air-transportable in a C-130 aircraft; the two extra-wide wanigans must be disassembled for shipment in this aircraft. A basic heating and ventilating kit, an electrical harness, and a slide-mounted fuel storage tank were developed for the wanigans. These are adequate for most general applications. Prototypes of both sled wanigans and both portable camp wanigans were tested and evaluated at polar field sites. These tests demonstrated that the sled wanigans are well suited for housing the facilities required on sled trail operations in polar regions, and that the portable camp wanigans are well suited for housing those facilities required at transient field camps and isolated construction sites.

KEY WORD	CLASSIFICATION
LOGISTICS	Transportation of Materials & Equipment Maintenance of Personnel

SOURCE

Earl and Wright Consulting Engineers
"Monopod Drilling Unit for the Beaufort Sea Specifications:
Construction and Outfitting"
Imperial Oil Limited
Calgary: Distributed by APOA, 1974
APOA Project No. 110: Conical and Cylindrical Gravity Structures
for Southern Beaufort Sea. Report No. 7

SUMMARY

These specifications and contract drawings are intended to contain the requirements and information governing the materials, construction, outfitting, equipping, and all appurtenances and their installation, of a complete seaworthy, bottom supported, enclosed drilling unit, ready for operation, to the Owner's requirements. ...The contract includes the supply and installation of all materials, labor, machinery, equipment, furnishings and fittings other than equipment and materials supplied by the Owner; and the installation of materials, machinery, equipment, furnishings and fittings supplied by the Owner. ...

KEY WORD	CLASSIFICATION
Construction Planning & Scheduling	Material & Equipment Selection

SOURCE

F.F. Slaney & Company
"Environmental Evaluation Summary of Construction and Construction
Support Activities Related to the Proposed Ten year Beaufort Sea
Offshore Exploration Program"
Imperial Oil Limited
Vancouver, B.C.

SUMMARY

(Volume I, the) summary volume contains a brief synopsis of the proposed 10-year exploration program, the key important points and conclusions from the supporting data contained in Volume II, and an identification of further environmental information requirements. ...Volume II is a detailed report by study discipline that provides a synthesis and evaluation of available information, a delineation of concerns related to the proposed construction programs, an impact assessment of probable short-term, long term and cumulative environmental impacts, and an identification of further information requirements for effective environmental protection planning. ...(This volume consists of 9 individually authored reports: part 1, Introduction, part 2. Climatology and Meteorology, Part 3, Physical - chemical, oceanography, part 4. Planktonic communities, part 5. Benthos, part 6. Fishes, part 7. Whales, part 8. Foxes, bears and seals, part 9.

KEY WORD	CLASSIFICATION
Construction Planning & Scheduling	Environmental Criteria

SOURCE

Girgrah, M., Shah, V.K. Department of Public Works Ottawa, Marine Directorate

"Construction of a Deep-Sea Dock in the Arctic"
Proceedings and 4th International Conference - POAC '77 1977

SUMMARY

The paper discusses the construction of the deep sea dock at Strathcona Sound, Baffin Island for the Nanisivik Mines Circular steel pile cells were constructed from a man-made ice platform. Details of construction procedures undertaken for pile driving is documented and illustrated with photographs.

The authors also discuss the functional and structural design of the dock.

KEY WORD	CLASSIFICATION
Construction Techniques	Equipment Selection and Utilization

SOURCE

Guzdar, Adi R.; Rhee, Sang Soon; Harvey, Andrew C.
Foster-Miller Associates Inc. Waltham Mass
"Design Data for the Development of Portable, Infrared
Radiant Heaters"
Corp. Source Codes: 142400
Report No: QM-6933; USA-NLABS-TR-73-14-GP
Sep. 72

SUMMARY

The purpose of this study was to develop the necessary design information for the development of a portable, gasoline-fired radiant heater to keep personnel and equipment warm in the Arctic environment. The heater is required to adequately heat a space 8 feet in diameter located from 4 to 10 feet from the heater, at an ambient temperature in the range of 0 to -50F and winds up to 20 mh. Focusing of the radiation emanating from the heater is considered essential to maintain high heating rates at these distances.

KEY WORD	CLASSIFICATION
LOGISTICS	Maintenance of Equipment Maintenance of Personnel

SOURCE

Hansen, R.W.; Sherwood, G.E.
"Pioneer Polar Structures. Erection of Portable
Maintenance Shelter"
Naval Civil Engineering Lab Port Hueneme Calif.
Corp. Source Codes: 000000
Report No: NCEL-N587
May 64

SUMMARY

This shelter was developed for the maintenance and repair of construction and other equipment in pioneer polar camps. The shelter, which is 20 by 24 feet, will accommodate equipment as large as a standard Size 4 tractor. It consists of a skid-mounted aluminum frame of knock-down construction and a canvas cover. Accessories include a gantry-mounted, 2-ton traveling hoist, and electrical harness, and a personnel side entry. An 8 by 20 foot skid-mounted wanigan outfitted with tools and shop equipment has been developed as a companion item for the shelter. This report provides a guide for erecting and outfitting the shelter and the wanigan. An electrical generator is not provided with the shelter and the wanigan. A 5-kw unit is required for this service. A heater is not provided for the shelter, but the wanigan is equipped with a 27,000-Btuh oil-fired space heater. The shelter is designed for heating with a portable fresh-air heater.

KEY WORD	CLASSIFICATION
LOGISTICS	Maintenance of Equipment

SOURCE

Hoffman, C.R.; Culbertson, T.L.
"Ice Construction - Investigation of Accelerated
  Bottom-Freezing Techniques"
Naval Civil Engineering Lab Port Hueneme Calif.
  Corp. Source Codes: 248150
  Report No: NCEL-TN-1078
  Feb 70

SUMMARY

Methods for improving the surface and structural characteristics of natural sea ice are needed to advance polar operational capabilities. Surface flood-freeze techniques are effective for improving floating ice sheets; accelerated bottom-freezing techniques are needed for constructing grounded and near-shore ice structures such as piers, docks and causeways at polar coastal bases. Investigations on accelerated bottom-freezing systems including field tests at Point Barrow Alaska, during the spring of 1969 showed that liquid convection cells have excellent potential for thickening, stabilizing and anchoring near-shore ice structures. Cells protruding through a natural ice sheet into seawater will produce ice along the entire length of cell with the ice production rate dependent upon the seawater temperature, the prevailing air temperature, and the thickness of the mass around the cell. For maximum ice growth, it was found that the cell should be of maximum size congruent with handling equipment and painted white to reflect solar radiation. It was concluded that additional laboratory and field tests should be conducted to improve cell performance and field aplication.

KEY WORD	CLASSIFICATION
Construction Techniques	Equipment Selection and Utilization

SOURCE

Pierce, N.E.; Sherwood, G.E.
"Polar Construction Equipment - Portable Floodlighting Unit"
Naval Civil Engineering Lab Port Hueneme Calif.
Corp. Source Codes: 248150
Report No: Ncel-Tr-348
3 Nov 64

SUMMARY

A sled-mounted floodlighting unit was developed to provide illumination and a portable lightduty power source for work areas away from main camps and construction sites in polar regions. It consists of a standard Army Quartermaster 400-pound-capacity manhaul sled, a lightweight 3-kw gasoline-engine-driven generator, and four light standards with three 150-watt lamps each. Evaluation of the unit in the Arctic has proved it to be well-suited for polar use. The sledmounted unit is easily towed by one man; it provides the required illumination of 1 footcandle at 100 feet within an included angle of 90 degrees; it is lightweight and compact for shipment by air; it is trouble-free; and the cost is reasonable. The unit is detailed in Y + D Drawing No. 993763 and is recommended as a standard item of construction equipment for polar operations.

KEY WORD	CLASSIFICATION
Equipment Selection & Utilization	Equipment Selection & Utilization

SOURCE

Shah, V.K. Marine Directorate, Public Works Canada, Ottawa.
"Strathcona Sound Wharf Repairs"
Presented at Marine Engineering Seminar, Rimouski, P.Q. 1972

SUMMARY

On August 31, 1981 a bulk carrier, m.v. Arctic, collided with the wharf inflicting extensive damage. The paper evaluates the damage and discusses the subsequent repairs undertaken. The paper is illustrated by several photographs.

KEY WORD	CLASSIFICATION
Construction Procedures and Techniques	Construction Techniques

SOURCE

Sherwood, G.E.; Moser Jr., E.H.
"Polar Structure - Design Concept for a Heavy Equipment Field
Repair Shelter"
Naval Civil Engineering Lab Port Hueneme Calif.
Corp. Source Codes: 000000
Report No: NCEL-N614
1 Jul 64

SUMMARY

The report presents the concept and design of a one/two-stall repair shelter for the maintenance and repair of equipment up to Size 6 snow tractors. A canvas-covered, arch-framed structure with steel members was used for the design. The shop area was located adjacent to the repair areas for convenience and efficiency and the entire shelter was mounted on skids for portability. The one-stall shelter and its outfitting will cost about $29,000; it will weigh about 30,500 pounds packaged for shipment. This cost is about 10 percent more and the weight is about 30 percent more than the portable maintenance shelter and its shop wanigan. The two-stall shelter and its outfitting will cost about $37,000; it will weigh about 41,400 pounds packaged for shipment. This cost is about 20 percent less and the weight is about 30 percent less than the temporary maintenance shelter. It is concluded that a prototype of the heavy-equipment field repair shelter should be evaluated at an outlying work center or construction project at an existing polar station.

KEY WORD	CLASSIFICATION
LOGISTICS	Maintenance of Equipment

SOURCE

Stachiw, Jerry D.; Hascall, Hudson L.C.; Sorensen, Marc
"Inflatable Igloo Shelter for Cold-Weather Operations"
(Research rept. Jul 72-Dec 73)
Naval Undersea Center San Diego Calif
Corp. Source Codes: 390458
Report No: NUC-TP-428
Dec 74

SUMMARY

The paper describes the design, fabrication and testing of an inflatable igloo shelter for cold-weather operations. Designed primarily to provide a lightweight, portable shelter for divers and operators of unmanned vehicles engaged in undersea search, rescue and salvage operations in the Arctic. The igloo is made of a sandwich fabric consisting of two layers of neoprene-coated nylon cloth tied together by a multitude of nylon threads. When the space between the two is pressurized with gas, they move apart to the full extent of the threads. Because the threads are closely spaced the fabric can endure a considerable gas pressure and when inflated is nearly as rigid as 1/4-inch-thick plywood. Two layers of sandwich fabric form the igloo wall, while a single layer serves as the floor. Each layer is three inches thick when inflated. The outer layer can be filled with water and allowed to freeze, creating a heavy capping of ice that anchors the igloo in very high winds.

KEY WORD	CLASSIFICATION
LOGISTICS	Equipment Selection & Utilization

SOURCE

Valentine, B.W.
"Self-Contained Sanitation Systems for 2- to 15-Man Polar Facilities"
Naval Civil Engineering Lab Port Hueneme Calif.
Corp. Source Codes: 248150
Report No: NCEL-TR-759
Mar 72

SUMMARY

Commercially available self-contained sanitation systems are compared with the NCEL Mechanical-Flush Chemical Toilet for use at Navy camps in polar regions. The basic process alternatives compared with the NCEL unit in a cost-effictiveness analysis are conventional chemical toilets, recirculating chemical toilets, incinerating toilers, and minimum-water flush toilet. Model 600 manufactured by Thetford Engineering Corp., Anaheim, California, was found to be the most cost-effective system suitable for use at 2- to 15-man polar pioneer camps.

KEY WORD	CLASSIFICATION
Environmental Criteria	Maintenance of Personnel

7.0 CASE HISTORIES

LIST OF TECHNICAL PUBLICATIONS

CASE HISTORIES

Title	Author	Publication	Publication Date	Page No.
A Steel Production Structure for the Alaskan Beaufort Sea Water Depths in the Beaufort Sea	Boaz, I. B. Bhula, D. N.	Thirteenth Annual Offshore Technology Conference 1981: proceedings - Dallas: Offshore Technology Conference, 1981, Vol. 3	1981	324
The Construction of Man-Made Drilling Islands and Sheetpile Enclosed Drillsites in the Alaskan Beaufort Sea	Galloway, D. E. Scher, R. L.	14th Annual OTC in Houston, Texas, May 3-6, 1982	1982	325

SOURCE

Boaz, I. B.; Bhula, D. N.
"A Steel Production Structure for the Alaskan Beaufort Sea"
Thirteenth Annual Offshore Technology Conference 1981:
proceedings - Dallas: Offshore Technology Conference,
1981, Vol. 3
OTC Paper 4113

SUMMARY

This paper describes the preliminary design of a steel production structure for use in the Alaskan Beaufort Sea. The Controlled Stiffness Steel Arctic Cone (COSSAC) is designed as an enclosed and fully integrated system. To minimize offshore hook-up time and costs, the entire structure is constructed and fully outfitted with production facilities in a graving dock and towed to its installation site. The structural design is based on the use of controlling relative stiffnesses of the primary structural members to distribute the concentrated load effects from multi-year ice features. This concept also results in lower temperature stresses than for a fully restrained system. The design has included the evaluation of forces and stresses due to ice, wind, waves, temperature changes, thaw subsidence as well as construction, transportation and installation effects.

KEY WORD	CLASSIFICATION
Case Histories	Steel Structures

SOURCE

Galloway, D. E.; Scher, R. L.
"The Construction of Man-Made Drilling Islands and Sheetpile Enclosed Drillsites in the Alaskan Beaufort Sea"
14th Annual OTC in Houston, Texas, May 3-6, 1982.

SUMMARY

This paper reviews the design and construction methods, and construction rates for Exxon Company, U.S.A.'s winter 1980-81 construction projects on the North Slope of Alaska. The projects include construction of 1) 90 miles of ice roads (ten-miles on floating ice), 2) two artificial (manmade) gravel islands off the Sagavanirktok River delta in ten-feet and 18 feet water depths, 3) two sheetpile enclosed drillsites on natural barrier islands approximately 60 miles east of Prudhoe Bay, and 4) the development of two upland gravel sources, one near Prudhoe Bay and one near Pt. Thomson.

For exploration drilling offshore in the Alaskan Beaufort Sea, it is important to be able to accurately evaluate alternative drillsites and plan for construction due to the present seasonal restrictions on drilling. The technology and experience gained during the exploration drillsite design and construction may be used during planning for future field development facilities and structures.

Emphasis is given to the unique design criteria and actual construction procedures and production rates for winter constructed manmade gravel islands and the sheetpile enclosed drillsites. These are the two principal alternatives being considered for exploration and development structures in shallow water.

KEY WORD	CLASSIFICATION
Case Histories	Drilling Islands

8.0 INSTRUMENTATION AND MONITORING

LIST OF ALL TECHNICAL PUBLICATIONS

INSTRUMENTATION

Title	Author	Publication	Publication Date	Page No.
Results of Model Ice Sheet Properties Research	Edwards, R. Y. Kotras, T. V.	Calgary: Distributed by APOA, APOA Project No. 40: Evaluation of Mechanical Properties of Saline Model Ice. Report No. 1, 2	1972	326
Surface Strain Measuring Instruments for Use on Sea Ice	Goodman, D. S.	Proceedings - Workshop on Sea Ice Field Measurement, St. John's, Newfoundland, April 29 - May 1, 1980/Compiled by Alastair J. Allan and David P. Bazeley, C-Core Publication 80-21	1980	327
In Situ Tests for Ice Strength Measurement	Kivisild, H. R, Iyer, S. H.	Ocean Engineering, Vol. 3, pp. 329-342. Pergamon Press 1976, Great Britian	1976	328
A Critical Survey of the Application of Borehole Logging Techniques to the Study of Sea Ice	Laidley, T. E.	St. John's, Newfoundland: Centre for Cold Ocean Resources Engineering, 1980. C-Core Publications,, No. 80-4. Technical Report - Memorial University of Newfoundland. Centre for Cold Ocean Resources Engineering	1980	329
Sea Ice Beam Tests of January 1975	Macy, R. L.	Calgary: Distributed by APOA, 1975 APOA Project No. 81: Ice Mechanics 1974-75, Arctic Field Test Program, Resolute Bay, N.W.T., Report No. 2	1975	330

SOURCE

Edwards, R. Y.; Kotras, T. V.
"Results of Model Ice Sheet Properties Research"
ARCTEC, Inc.
Calgary: Distributed by APOA, 1972
APOA Project No. 40: Evaluation of Mechanical Properties of
Saline Model Ice. Report No. 1, 2

SUMMARY

This report describes the results of experiments to demonstrate that the mechanical properties of model ice sheets formed in the ARCTEC Ice Model Basin may be controlled within the range required for proper modeling of ice sheet-offshore structure interactions. The salinity, temperature and thickness of model ice sheets were varied widely. The mechanical properties (flexural strength, elastic modulus, and shear strength) were measured in these sheets. The results of the analysis of this data indicate that the ratio of elastic modulus to flexural strength may be maintained at a level in excess of 1000 for flexural strengths as low as 0.1 kg/sq. cm. This implies that modeling ice sheet structure interactions at scales as low as 1/70th is feasible.

KEY WORD	CLASSIFICATION
Instrumentation	Model Ice Sheet Properties

SOURCE

Goodman, D. S.
"Surface Strain Measuring Instruments for Use on Sea Ice"
Proceedings - Workshop on Sea Ice Field Measurement, St. John's
April 29 - May 1, 1980/Compiled by Alastair J. Allan and David P.
Bazeley, C-Core Publication 80-21

SUMMARY

This paper presents the detailed designs of two instruments the Cavendish and Scott Polar Research Institute have used for surface strain measurements on glaciers and sea ice. ...The wire strainmeter, to be described, was adapted for use on ice from a design by Roger Bilham of the Dept. of Geodesy and Geophysics of the University of Cambridge (Bilham, 1970). He designed the instrument for the measurement of Earth Tides, which typically require a resolution of strain amplitude of the order of .0000001. The second instrument, the rod strainmeter, was developed to provide a more robust and portable instrument with a resolution of the order of .0000001. Our purpose has been to measure the small strain changes which result from the deformation of sea ice due to swell or the change of shape of a glacier as it moves down a slope: for which these two instruments have been successful. ...In the paper the technical details of the two instruments and the associated amplifier system with their limitations will be described. ...

KEY WORD	CLASSIFICATION
Instrumentation	Surface Strain Measurements

SOURCE

Kivisild, H. R.; Iyer, S. H.
"In Situ Tests for Ice Strength Measurements"
Ocean Engineering, Vol. 3, pp. 329-342. Pergamon Press 1976, Great Britian

SUMMARY

Ice effects have caused extensive damage. Enormous forces have been recorded. On the other hand, ice has been used as a structural material under various situations. To use ice beneficially and to assess the danger of ice forces, it is necessary to know the mechanical properties of ice.

Results from the large number of ice tests carried out in laboratories show the difficulties of sampling and testing procedures. Most of the tests have not reproduced faithfully enough the conditions existing in nature. To obtain adequate results, laborious and slow samplings and preparations of test specimens have been necessary. Recently, extensive use has been made of in situ tests in order to reduce the number of factors which can induce errors in measurements. Large scale tests have simulated actual structures. General ice properties have become available from small-scale in situ tests. Since these tests give rapid results, a large number are already available with a good coverage of field conditions.

KEY WORD	CLASSIFICATION
Instrumentation	In Situ Tests of Ice Strength

SOURCE

Laidley, T. E.
"A Critical Survey of the Application of Borehole Logging Techniques
to the Study of Sea Ice"
St. John's, Newfoundland: Centre for Cold Ocean Resources
Engineering, 1980.
C-Core Publication, No. 80-4
Technical Report - Memorial University of Newfoundland.
Centre for Cold Ocean Resources Engineering

SUMMARY

The theory of several borehole logging techniques is reviewed and their suitability for the measurement of the physical, chemical and mechanical properties of sea ice and pressure ridges is assessed. Four different borehole technologies were studies; nuclear, electrical, acoustic and hydraulic. The underlying operating principle of each technique is used to evaluate the instrument's sensitivity and their response to the expected values and variations of the sea ice parameters. Most techniques investigated were found to lack either the vertical resolution or sensitivity necessary to profile an ice sheet or pressure ridge. Recommendations are made for further studies of the hydraulic fracturing technique and the borehole televiewer.

KEY WORD	CLASSIFICATION
Instrumentation	Borehole Logging Tests

SOURCE

Macy, R. L. Sun Oil Company Limited
"Sea Ice Beam Tests of January 1975"
Calgary: Distributed by APOA, 1975
APOA Project No. 81: Ice Mechanics 1974-75, Arctic Field Test
 Program, Resolute Bay, North West Territories
 Report No. 2
Original Publisher: Sun Oil Company Limited

SUMMARY

The purpose of these tests was to determine the strength and deflection characteristics of Arctic sea ice when broken as a cantilever beam. ...Four cantilever beams were broken by pulling upward on the free end. The beams were in place in Resolute Bay in the Canadain High Arctic. Instrumentation provided displacement and applied load information as a function of time. A load frame utilizing a hydraulic ram carried the up-load from the free end of the beam to the surrounding ice.

KEY WORD	CLASSIFICATION
Instrumentation	Ice Beam Tests

APPENDIX 1

LIST OF AGENCIES AND ORGANIZATIONS

1. American Concrete Institute
P.O. Box 19150
Detroit, Michigan 48219

2. American Geophysical Union
1909 King St. N.W.
Washington, D.C.
20006

3. American Petroleum Institute
2101 L St., N.W.
Washington, D.C.
20037

4. American Society of Civil Engineers
345 E. 47th St.
New York, N.Y. 10017

5. American Welding Society
2501 N.W. Seventh St.
Miami, Florida 33125

6. Arctic Environmental Information and
Data Center, University of Alaska,
707 A Street, Anchorage, Alaska
99501, Telephone (907) 279-4253

7. Arctic Institute of North America, Second
Floor, Library Block, University of
Calgary, 2500 University Drive
N.W., Calgary, Alberta T2N 1N4
Telephone (403) 284-5966

8. Arctic Petroleum Operators' Association
727-6th Avenue, S.W.
Suite 1902
Calgary, Alberta T2P 0V1

9. Bedford Institute of Oceanography,
Ocean and Aquatic Sciences,
Atlantic, P.O. Box 1006,
Dartmouth, Nova Scotia
B2Y 4A2. Telephone (902) 426-3675

10. Boreal Institute of Northern Studies
University of Alberta,
Edmonton, Alberta T6G 2E9.
Telephone (403) 432-4409

11. Canada Centre for Inland Waters
Inland Water Directorate
867 Lakeshore Road, P.O. Box 5050
Burlington, Ontario L7R 4A6

12. Canada Oil and Gas Lands Administration
Tower "B", Place Vanier
355 River Road
Vanier, Ontario

13. Canadian Society for Civil Engineering
Suite 700
2050 Mansfield St.
Montreal, P.Q. H3A 1Z2

14. Çentre d'Ingénierie Nordique (CINEP)
Ecole Polytechnique,
Campus de l'Université Montréal, Montréal
Québec H3C 3A7.
Telephone (514) 344-4932

15. Churchill Research Centre Inc.,
600 - 428 Portage Avenue,
Winnipeg, Manitoba R3C 0E4
Telephone (204) 949-1844

16. Det Norske Veritas
P.O. Box 300
N-1322 Horvik, Norway

17. Engineering Institute of Canada
700 EIC Building
2050 Mansfield St.
Montreal, P.Q. H3A 1Z2

18. Environmental Protection Service
Environment Canada
Ottawa, K1A 1C8

19. Freshwater Institute
501 University Crescent
Winnipeg, Manitoba
R3T 2N6
Telephone (204) 269-7379

20. Government In-Service Library
Government of the Northwest Territories
Yellowknife, Northwest Territories X1A 2L9
Telephone (403) 874-6531

21. Institute of Ocean Sciences
9860 West Saanich Road
Sidney, B.C.
V8L 4B2

22. Inuvik Scientific Resource Centre
Box 1430
Inuvik, N.W.T. XEO OTO
Telephone (403) 979-3838

23. National Research Council of Canada
Montreal Rd.
Ottawa, Ontario
K1A OR6

24. Northern Studies Library
McGill University
1020 Pine Avenue West
Montréal, Québec
H3A 1A2
Telephone (515) 392-8233

25. Norwegian Institute of Technology
University of Trondheim
7034 Trondheim-NTH
Norway

26. Ocean Engineering Information Centre
Memorial University of Newfoundland
St. John's Newfoundland
A1B 3X5
Telephone (709) 737-8377

27. Scott Library
York University
4700 Keele Street
Downsview, Ontario
M3J 2R2

28. Scott Polar Institute
University of Cambridge
Cambridge, England
CB2 1ER

29. University of Alaska
Alaska and Polar Regions Dept.
Elmer E. Rasmuson Library
University of Alaska
Fairbanks 310 Tanana Drive
Fairbanks, Alaska U.S.A. 99701

30. U.S. Army Corps of Engineers
The Adjunct General, HQDA (DAAG-PAD-1)
Washington, D.C. 20314

31. U.S. Army Cold Regions Research and
Engineering Laboratory
72 Lyme Road
Hanover, New Hampshire
U.S.A. 03755
Telephone (603) 643-3200 ext. 238 or 221

32. The Yukon Archives and Records Services
2nd Avenue and Hawkins Street
Box 2703
Whitehorse, Yukon Territory Y1A 2C6
Telephone (403) 667-5321

33. World Data Centre A for Glaciology
CIRES, Campus Box 449
University of Colorado
Boulder, Colorado
U.S.A. 80309

34. Major Data Bases covering the literature on Cold Regions

- Arctic Science and Technology System (ASTIS)

  Produced by the Arctic Institute of North America at the University of Calgary, this data base provides access to information concerning the North American Arctic, as well as, northern Scandinavia and the U.S.S.R. and cold regions generally. The earth sciences, life sciences, engineering and technology are some of the subject areas included.

- Canada Institute for Scientific and Technical Information - Current Catalogue (CON)

  Available on OON, this data base includes monographs, conferences and technical reports received by CISTI and its branches since roughly 1978.

- Cold Regions

  Produced by the Cold Regions Research and Engineering Laboratory, this data base corresponds to the printed publications "Antarctic Bibliography" and "Bibliography on Cold Regions Science and Technology".

- Compendex

  The online version of Engineering Index, this data base covers all aspects of engineering on a world-wide basis.

- Ntis

  This source provides access to U.S. government-sponsored research, development and engineering reports.

- Delft Hydraulics Laboratory

APPENDIX 2

LIST OF USEFUL REFERENCES

LIST OF USEFUL REFERENCES

The following is a list of publications which do not appear in the annotated bibliography section of this Volume 2. Reference to many of these publications, as cross-referenced in Volume 1, has been made. Others are being presented as additional information to the users of this handbook.

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4. American Petroleum Institute
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API Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms, API RP2A, 12th edition, 1982.

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"Simulation of the Curing Conditions of a Slipformed Concrete in the Arctic Sea"
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"Beaufort Sea Heat Loss Prior to Freeze Up", in Proceedings of the 7th International Conference on Port and Ocean Engineering under Arctic Conditions, POAC '83, Helsinki, Finland, April 5-9, 1983.

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APPENDIX 3

LIST OF CONFERENCES

Canadian Hydrotechnical Conference; held biennially, organized by the Canadian Society of Civil Engineering; 6th Conference, 1983, held in June at the University of Ottawa.

International Association for Hydraulic Research; congresses held biennially.

International Conference on Permafrost; more information can be obtained from the National Academy of Sciences, Washington, D.C., 4th conference, 1983, held in July at the University of Alaska at Fairbanks, Alaska.

International Conference on Port and Ocean Engineering Under Arctic Conditions; held biennially; sponsorship and organization varies with each conference. 7th conference, 1983, held in Helsinki. Information on upcoming conferences is available from either the International Council of Scientific Unions or the Union of International Engineering Organizations.

International Offshore Mechanics and Arctic Engineering Symposium; held annually; proceedings published by the American Society of Mechanical Engineers, New York, N.Y., 3rd conference, 1984, held February 12-17, New Orleans, Louisiana.

MIT Sea Grant College Program Lectures Seminars; held annually; organized by and held at the Massachusetts Institute of Technology, Cambridge, Mass.

Offshore Technology Conference; held annually; in Houston, Texas; organized by the Offshore Technology Conference.

APPENDIX 4

COMPANIES PROVIDING SEALIFT TRANSPORTATION IN THE CANADIAN ARCTIC

P.O.L. TANKERS

Société Sofati-Soconav
101 Montcalm St.
P.O. Box 540
Sorel, Quebec
J3P 5P4

Attn: Guy Bazinet
Tel.: (514) 742-5621
Telex: 05-267671

Gulf Canada Ltd.
800 Bay St.
Toronto, Ontario
M5S 1Y8

Attn: K.J. Shanahan
Tel.: (416) 924-4141
Telex: 065-24298

Halco Inc.
155 University Ave.
Suite 701
Toronto, Ontario
M5H 3B7

Attn: F.M. Shearstone
Tel.: (416) 362-2648
Telex: 065-24172

Irving Oil Limited
10 Sydney
P.O. Box 1421
St. John, N.B.

Attn: W.A. London
Tel.: (506) 657-7722
Telex: 014-47273

Texaco Inc.
Wynford Drive
Don Mills, Ontario

Attn: E.R. Pirie
Tel.: (416) 441-7499
Telex: 069-66742

Imperial Oil Co. Ltd.
1961 Merivale Road
Nepean, Ontario
K2G 1G1

Attn: Clare Langdon
Tel.: (613) 225-7662
Telex: 053-3613

Federal Commerce & Navigation Co. Ltd.
600 de la Gauchetière St. W.
Suite 2600
Montreal, Quebec
H3B 4M3

Attn: Pat O'Reilly
Tel.: (514) 878-6500
Telex: 055-60637

C.A. Crosbie Shipping Ltd.
276 St. Jacques St.
Suite 822
Montreal, Quebec
H2Y 1N3

Attn: Fred Taylor
Tel.: (514) 849-6194
Telex: 055-61976

Shell Canada Limited
505 University Ave.
Box 400, Terminal 'A'
Toronto, Ontario
M5W 1E1

Attn: D.F. Main
Tel.: (416) 597-7111
Telex: 062-19612

Transworld Shipping Ltd.
363 St. François Xavier St.
Suite 300
Montreal, Quebec
H2Y 3P9
Attn: Bart Malott
Tel.: (514) 845-9151
Telex: 05-25266

Petrocan
1 Place Ville Marie
Montreal, Quebec
H3B 4A9
Attn: Mr. McKinnon
Tel.: (514) 878-7231
Telex: 052-67593

Mount Royal Marine Repairs Ltd.
P.O. Box 250, Station 'C'
Montreal, Quebec
H2L 4K1
Attn: Gail Jorgensen
Tel.: (514) 844-1071
Telex: 052-4530

Boreal Navigation Inc.
3236 Chemin St-Louis
Ste-Foy, Quebec
G1W 1S2
Attn: Yvon Dufour
Tel.: (418) 653-6055
Telex: 051-31708

March Shipping Limited
360 St. James St. W.
Suite 1400
Montreal, Quebec
H2Y 1P5
Attn: Raymond Boissonneault
Tel.: (514) 842-8841
Telex: 05-25246

Dome Petroleum Limited
Canadian Marine Drilling Ltd.
400 5th Ave. S.W.
P.O. Box 200
Calgary, Alberta
T2P 2H8
Attn: Garth Harrison
Tel.: (403) 232-5100
Telex: 038-22062

Liquitransport Distribution Inc.
625 President-Kennedy
Suite 1201
Montreal, Quebec
H3A 1K2
Attn: Capt. G. Iskander
Tel.: (514) 284-9666
Telex: 05-25152

Jensen Shipping Limited
465 St. Jean St.
Suite 1005
Montreal, Quebec
H2Y 2R6
Attn: Niels Jorgensen
Tel.: (514) 849-5691
Telex: 055-62405

Atlantic Marine Shipping Corp.
Division of Metro Marine Transport
and Terminals Ltd.
P.O. Box 6000
636 St. George St.
Moncton, N.B.
E1C 9E1

Attn: Shirley Agnew
Tel.: (506) 389-3525

SEALIFT - DRY CARGO

Canada Steamship Lines
759 Victoria Square
Montreal, Quebec

N.M. Paterson & Sons (Quebec) Ltd.
818 Insurance Exchange Bldg.
Montreal, Quebec
H2Y 1N3

Logistec Navigation Inc.
360 St. Jacques St. W.
15th Floor
Montreal, Quebec
H2Y 1P5

March Shipping Ltd.
360 St. Jacques St. W.
Suite 1400
Montreal, Quebec
H2Y 1P5

Halco Inc.
155 University Ave.
Suite 701
Toronto, Ontario
M5H 3B7

Federal Commerce & Navigation Co. Ltd.
600 de la Gauchetière ouest
Suite 2600
Montreal, Quebec
H3B 4M3

Transport Maritime Harvey Ltée
360 St. Jacques St.
Suite 414
Montreal, Quebec
H2Y 1B5

Transport Desgagnês Inc.
250 Grande Allée ouest
Suite 800
Quebec City, Quebec
G1R 2H4

McAllister Towing & Salvage Ltd.
410 St. Nicholas St.
Montreal, Quebec
H2Y 2P5

Eastern Canada Shipping Ltd.
1405 Blvd. Industriel
Laprairie, Quebec
J5R 2E4

Vipcon General Contractor
1150 Marie Victorin
Longueuil, Quebec

Carino Co. Ltd.
33 Fagon Drive
St. John's, Nfld.
A1C 5X8

Jensen Shipping Ltd.
465 St. Jean St.
Montreal, Quebec
H2Y 2R6

C.A. Crosbie Shipping Ltd.
276 St. Jacques St. W.
Suite 822
Montreal, Quebec
H2Y 1N3

Transport Navimex Canada Inc.
53 St-Pierre
Quebec City, Quebec
G1K 3Z7

Boreal Navigation Inc.
3236 Chemin St-Louis
Ste-Foy, Quebec
G1W 1S2

Transworld Shipping Ltd.
363 St. François-Xavier
Room 230
Montreal, Quebec
H2Y 3P9

C.R. Ward
9839 Fourth St.
Sidney, B.C.
V8L 3W6

Baffin Enterprises Ltd.
1019 Nelson Street
Oshawa, Ontario
L1H 7N9

Ungava Navigation Ltée
276 St. Jacques ouest
Suite 100
Montreal, Quebec
H2Y 1N3

Puddister Trading Co. Ltd.
P.O. Box 38, Station 'C'
23 Springdale St.
St. John's, Nfld.
A1C 5H5